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Near Field Pressure Fluctuations in the Exit Plane of a Choked Axisymmetric Nozzle

Michael K. Ponton, John M. Seiner, and Martha C. Brown

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Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Summary

Near field pressure data are presented for an unheated jet issuing from an underexpanded sonic nozzle for two exit lip thicknesses of 0.200 and 0.625 nozzle diameters. Because both the amplitude and the frequency of the screech mechanism have been shown to be sensitive to the initial nozzle exit geometry, the data presented are at nozzle operating conditions where screech is dominant in the acoustic emission. Fluctuating measurements were obtained on the nozzle exit surface as well as in the acoustic near field. These measurements can be used to better characterize the initial acoustic shear layer excitation due to the natural screech feedback process. Such a characterization would be useful in the development of active control methodologies, incorporated in the nozzle exit plane, that can reduce the presence of screech.

Introduction

The acoustic emission from supersonic shock-containing jets may be dominated by an intense tonal component referred to as screech. Such a domination is dependent on the thermodynamic operating conditions of the nozzle and the angle of measurement. The seminal work of Powell [1] described screech as being associated with a feedback process as follows: (a) an embryonic disturbance is shed in the initial shear layer region of the jet; (b) the disturbance is amplified as it convects downstream; (c) the amplified disturbance interacts with the shock cell system causing plume oscillation; (d) the oscillation produces sound; and (e) the sound propagates upstream toward the nozzle exit and excites the initial shear layer thus closing the feedback loop.

Experimental work [2, 3] suggest that free shear flows contain organized wavelike structures in addition to the random turbulent fluctuations. Because the spatial magnitude of these structures are of orders near that of the mean flow, they are referred to as large-scale structures and also as

instability waves due to their local wavelike characteristics [4]. Tam, Seiner and Yu [5] introduced the use of linear spatial stability theory to describe the relationship between screech and the large scale turbulent structure of the jet.

Seiner [6] indicates that the frequency of the most highly amplified instability wave is the same as that measured for screech. Thus, a better understanding of the screech mechanism can be derived from Schlieren investigations of the large scale structures [7, 8, 9, 10] as well as with acoustic measurements [9, 11, 12, 13, 14, 15]. The screech mechanism has been extensively studied for a variety of nozzle geometries that include rectangular [8, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 15], asymmetric [26, 20], multiple jet [27, 28, 29, 30], and axisymmetric [1, 7, 31, 32, 33, 14].

Numerous investigations continue to exist to reduce the presence of screech. These studies are not purely academic: full scale studies [34] have shown significant acoustic energy associated with this noise mechanism causing, in some cases, sonic fatigue of airborne structures [35]. To facilitate their study of broadband shock associated noise, Harper-Bourne and Fisher [36] introduced tabs into the initial shear layer region of the jet to reduce the screech "tones." They also performed investigations into the effects on the screech amplitude of an acoustic reflector placed in the nozzle exit plane. Denham [37] demonstrates reductions in the screech amplitude using acoustic excitation and Norum [38] shows that screech can be modified by incorporating slots in choked tube jets. More recently, Huang et al. [39] are using electrostatic microactuators to control screech.

The purpose of this report is to provide data which can be used to better understand the initial acoustic shear layer excitation due to the screech feedback process. With this understanding, future investigators will be in a better position to modify the screech cycle via modifications to the initial nozzle conditions.

Symbols

D	inside diameter of the nozzle exit
M_j	fully expanded Mach number based on nozzle pressure ratio
R	distance from the sensor to the nozzle centerline
SPL	sound pressure level, dB, in a 25 Hz band (re 20 μ Pa)
λ_s	acoustic wavelength of screech

Experimental Details

The experiment was conducted in the Anechoic Noise Facility (ANF) [40] at the NASA Langley Research Center. The interior dimensions of the ANF are 27.5 ft by 27 ft by 24 ft high within the acoustic wedge tips. The anechoic treatment minimally absorbs 99% of the incident sound for frequencies in excess of 100 Hz. The ANF is capable of supplying dry unheated air for continuous operation and the electronically controlled valves maintain the nozzle pressure ratio to within 0.3% of the desired set point. All pressure transducers used by the flow control system received daily calibration.

The nozzle assembly consisted of a contoured transition section connecting a 7.875 inch inside diameter supply air pipe to a 1.500 inch inside diameter pipe which then led to the nozzle. The 1.500 inch straight section was 26.000 inches in length with an outside diameter of 2.250 inches. The length of this assembly allowed minimal interference of flanges with the natural jet entrainment. The nozzle was convergent and conical (5° convergence angle) with an exhaust diameter of 1.000 inches. High precision collars were fabricated which, when placed over the nozzle exit, would increase the nozzle exit lip

thickness to 0.200 and 0.625 inches as indicated in Figure 1 (shaded regions). Note that great care was taken to minimize exterior nozzle assembly protrusions.

The near field acoustic spectra were obtained by a single 1/4 inch microphone and surface-mounted transducers on the nozzle exit lip. The microphone was located in the nozzle exit plane and positioned 2 inches from the centerline. Because the directivity of screech is at shallow angles to the jet axis, the near field microphone is located in a position at which the measurement of screech should easily be obtained for all nozzle pressure ratios investigated. The included angle between the microphone and nozzle axes was approximately 6° . The diameter of the surface-mounted pressure transducers were 0.095 inches and their positions are indicated in Figure 2.

The length of the nozzle assembly created a total pressure loss through the system. Thus, before the experiment was conducted the total pressure exiting the nozzle was measured and a relationship found between the actual total pressure and the pressure measured in the stagnation chamber leading to the nozzle assembly. The fully expanded Mach number, M_j , was based on the true nozzle pressure ratio (actual total pressure divided by the ambient pressure) by using their isentropic relationship.

Acoustic Results

Narrowband spectra were gathered for each sensor utilizing a Fast Fourier Transform analyzer set to a filter bandwidth of 25 Hz and a maximum frequency of 20 kHz. For the 0.625 inch lip thickness, 44 M_j values ranging from 1.04 to 1.90 were tested. Thirty one M_j values ranging from 1.04 to 1.64 were investigated for the 0.200 inch lip thickness (screech does not dominate acoustic spectra at high Mach numbers for thinner lip configurations). The data are presented by the desired fully expanded Mach number. Figures 3 through 46 are for the 0.625 inch lip and figures 47 through 77 are for the

0.200 inch lip thickness. Each figure contains all sensor spectra acquired and indicated using the respective R/D position.

Presented in figures 78 through 82 are the normalized acoustic wavelength and the corresponding sound pressure levels for some of the dominant screech components. The wavelength was computed using the ambient speed of sound. The data are for fundamental frequencies and not harmonics. Figures 78 through 80 are for the 0.625 inch lip and figures 81 and 82 are for the 0.200 inch lip thickness.

Concluding Remarks

Near field pressure data acquired at the NASA Langley Research Center are presented for a convergent conical nozzle operating underexpanded. Two exit lip thicknesses of 0.200 and 0.625 nozzle diameters were tested. The fully expanded Mach number range tested for each lip thickness was limited to the operating conditions that screech is the dominant noise source mechanism. Narrowband spectra are given for a single near field microphone located in the nozzle exit plane as well as fluctuating pressure measurements acquired on the nozzle exit. These measurements may prove useful in understanding the initial acoustic jet excitation due to the screech mechanism. Such information would be valuable in the development of active screech control methodologies.

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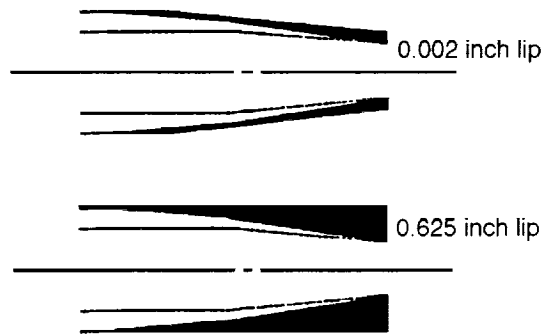


Figure 1. Position of collars (shaded regions) on the nozzle exterior

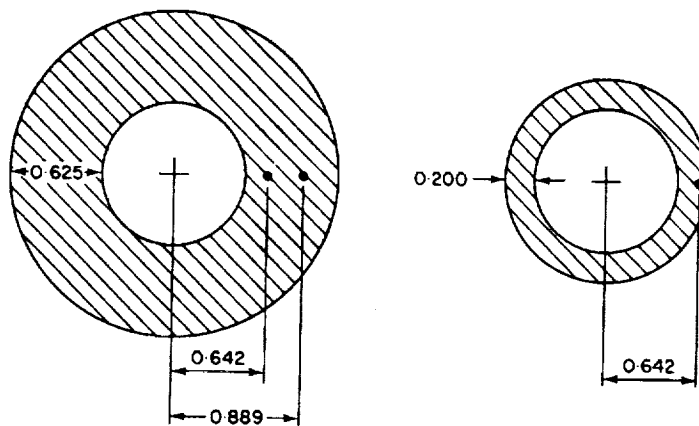
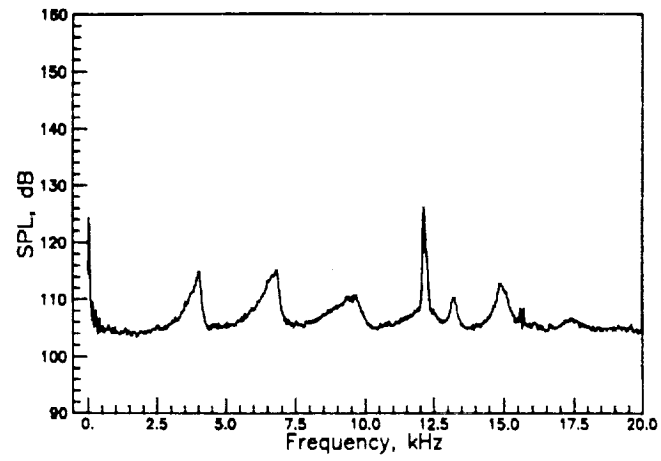
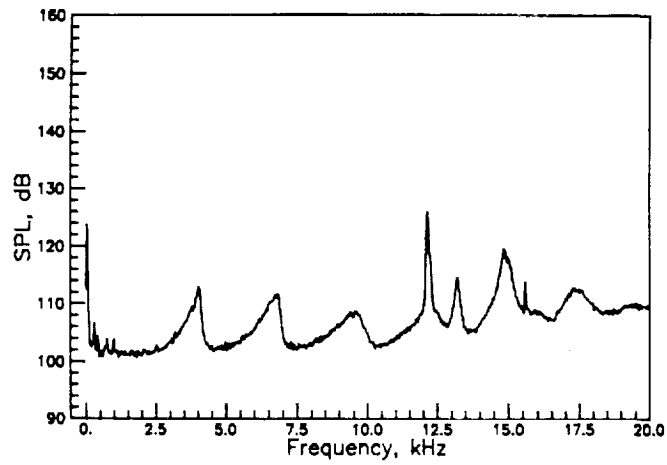


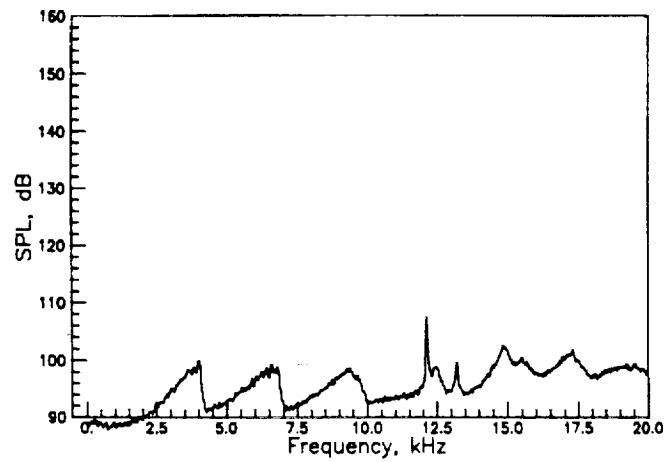
Figure 2. Location of surface-mounted transducers on the nozzle exit lip (dimensions in inches).



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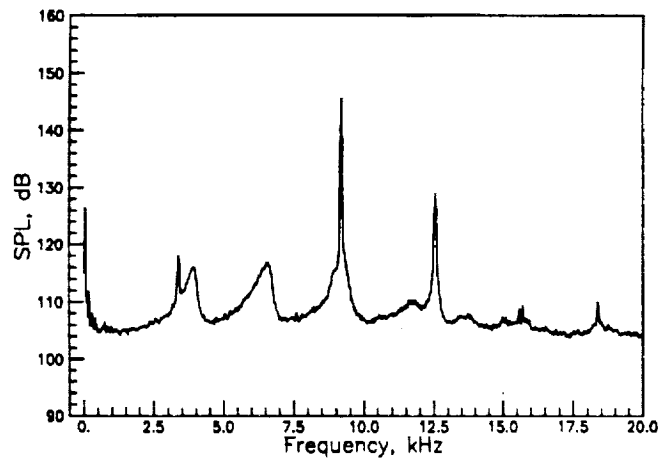


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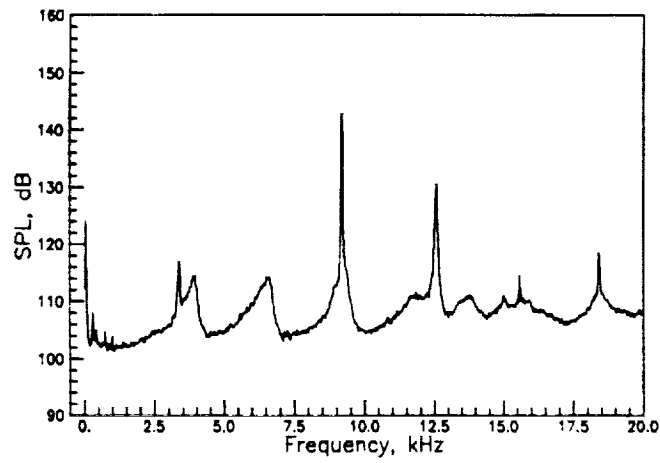


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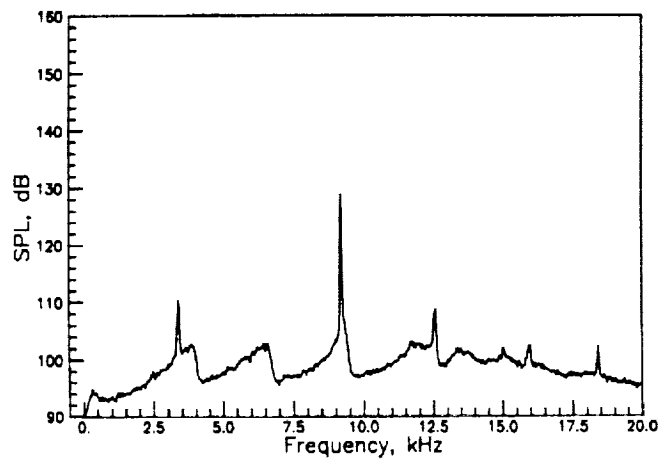
Figure 3. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.04$.



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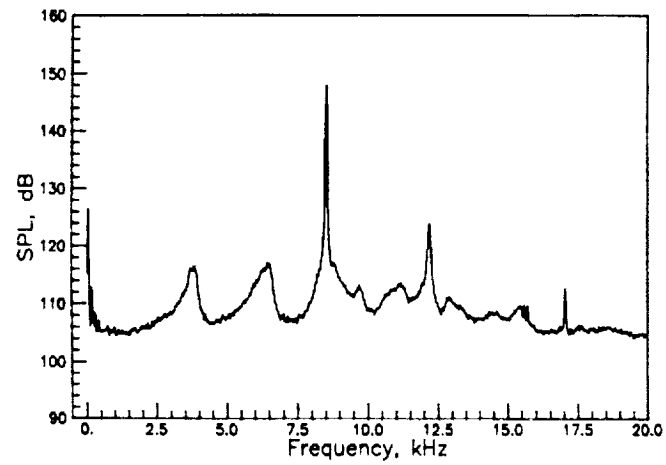


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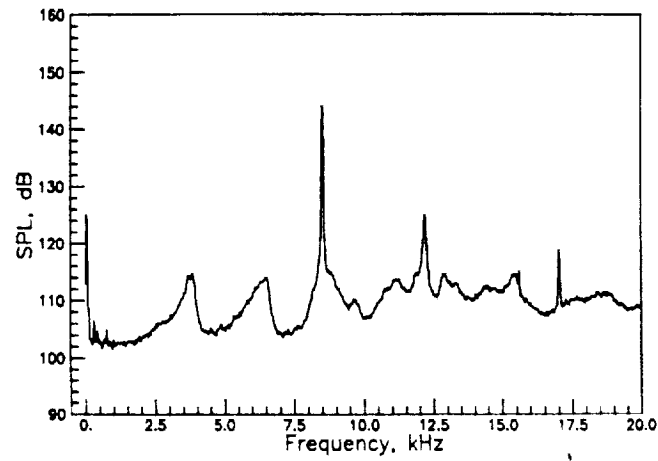


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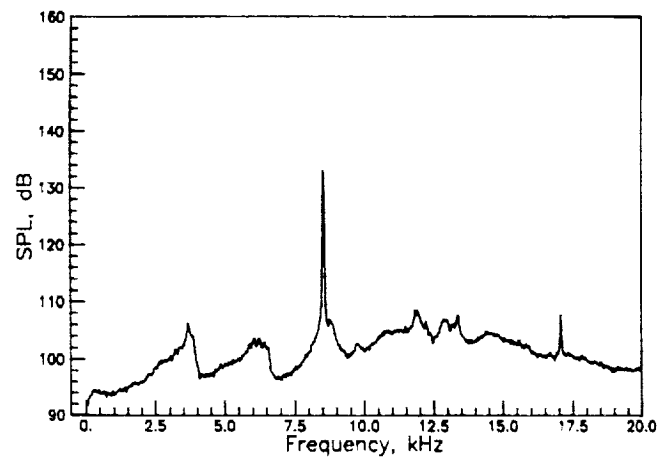
Figure 4. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.07$.



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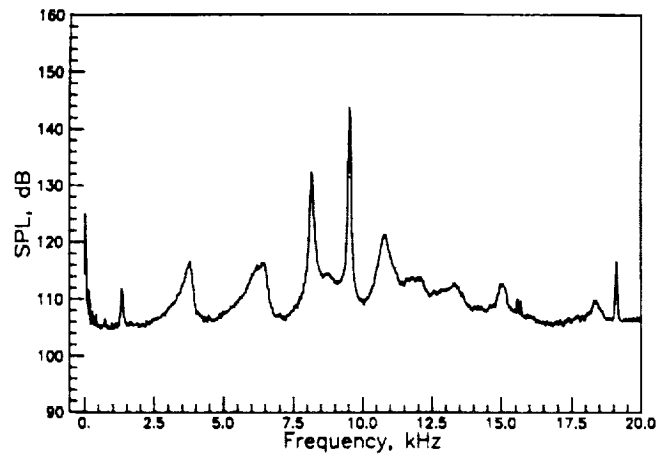


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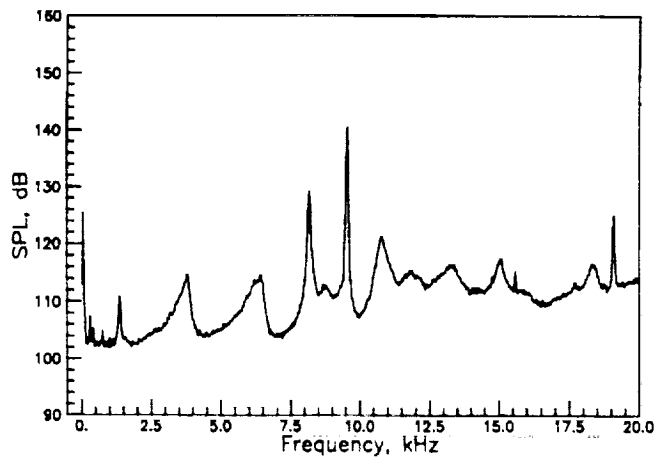


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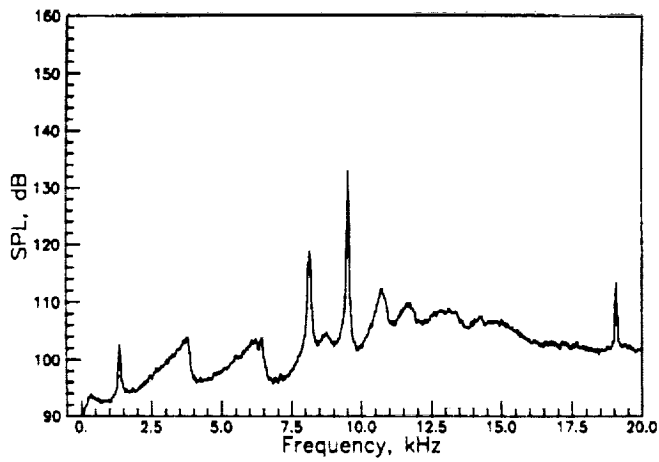
Figure 5. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.09$.



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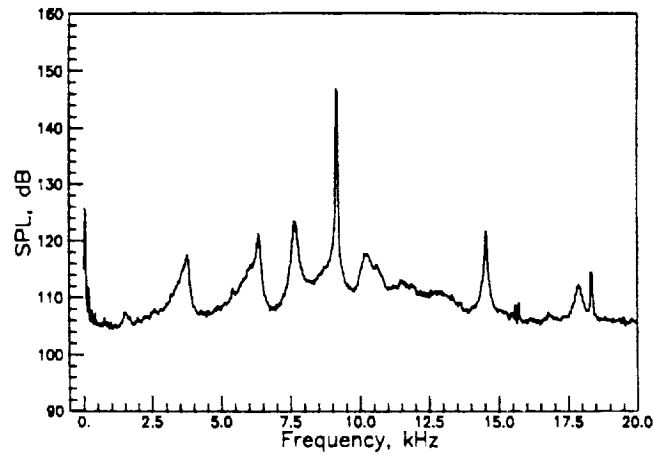


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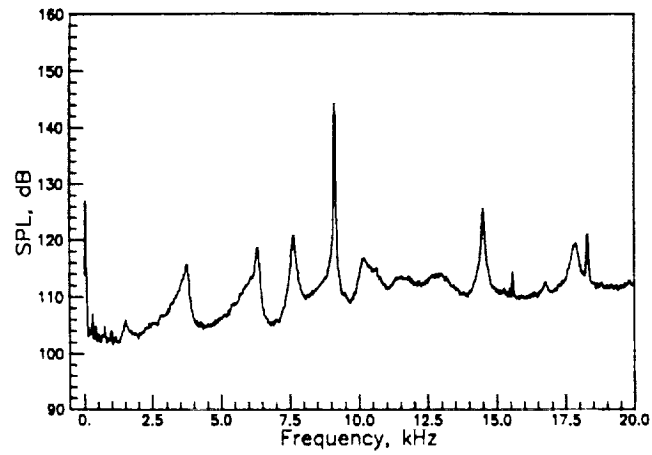


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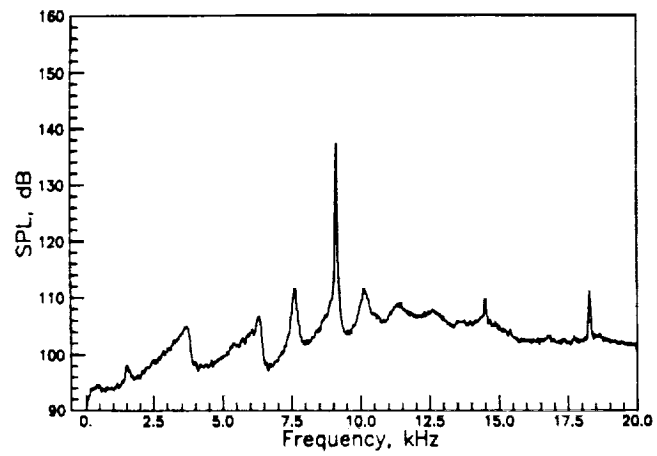
Figure 6. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.11$.



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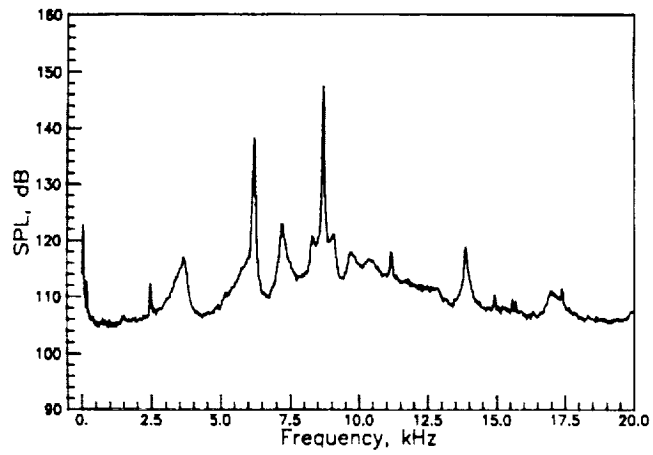


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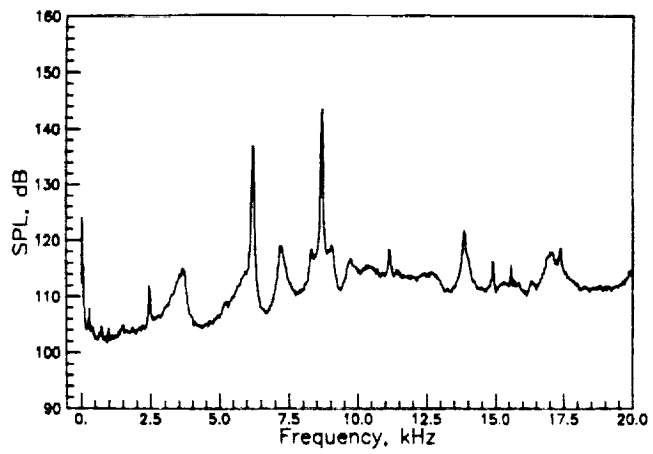


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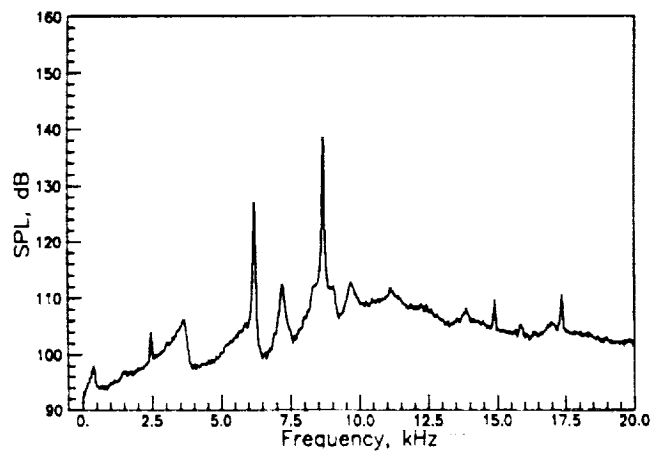
Figure 7. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.13$.



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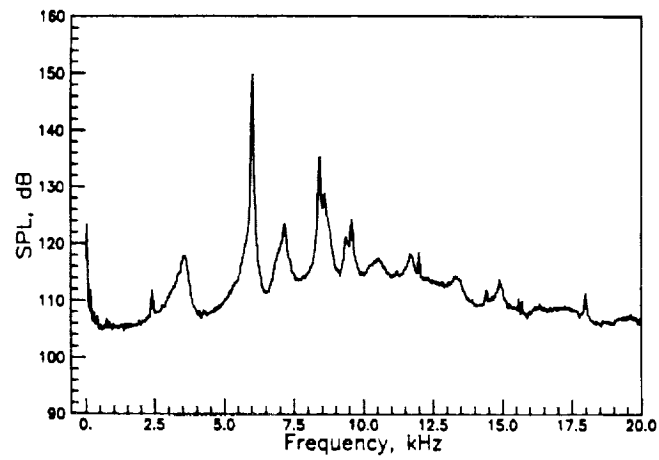


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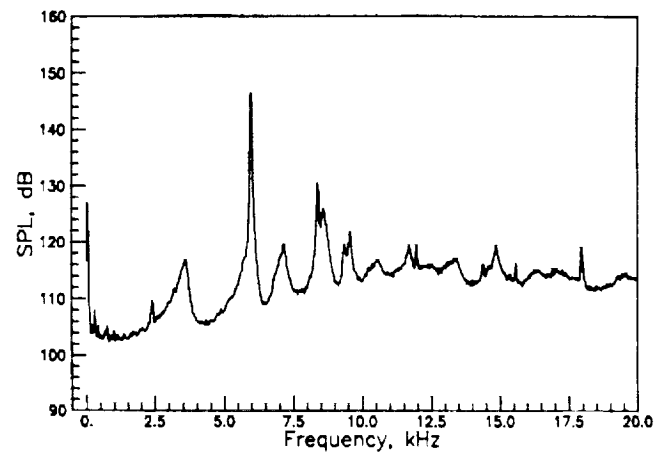


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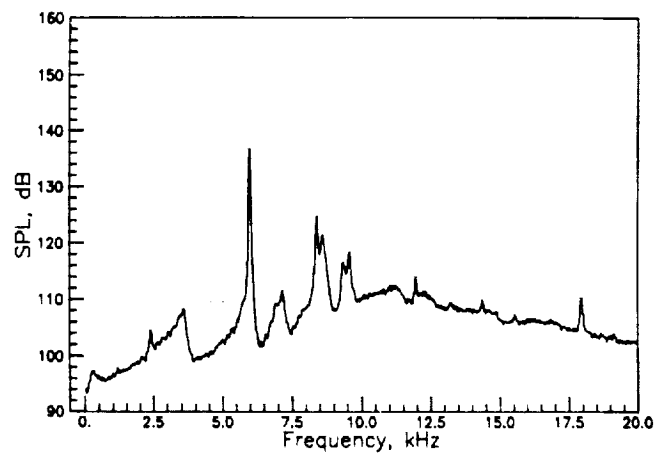
Figure 8. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.15$.



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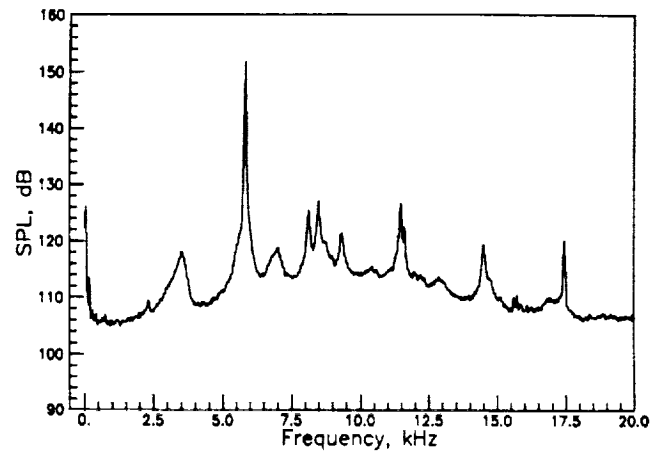


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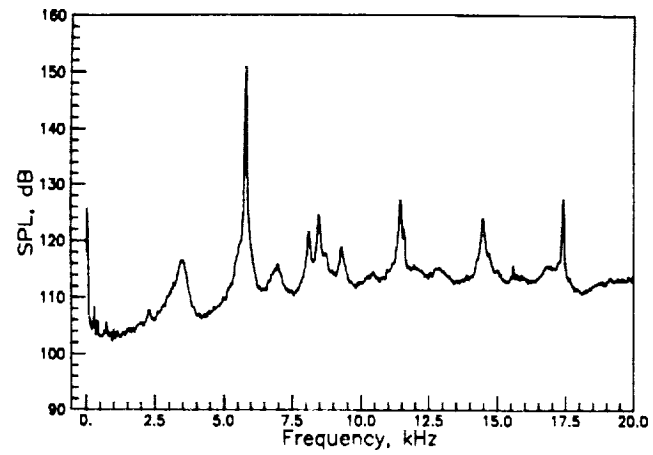


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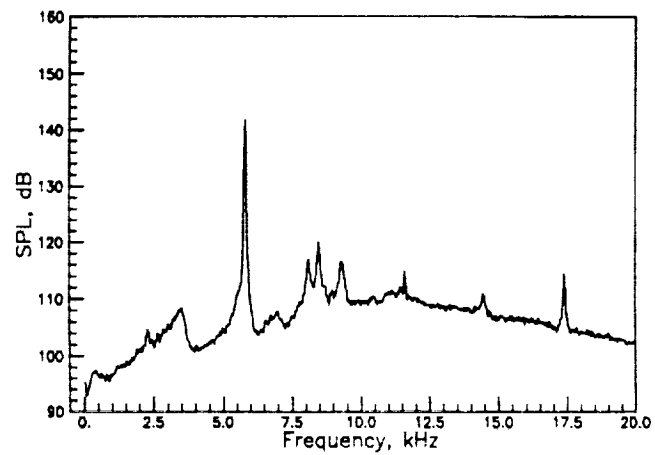
Figure 9. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.17$.



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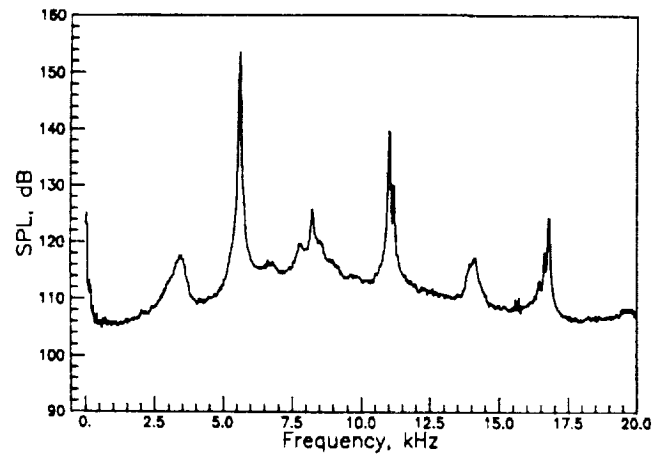


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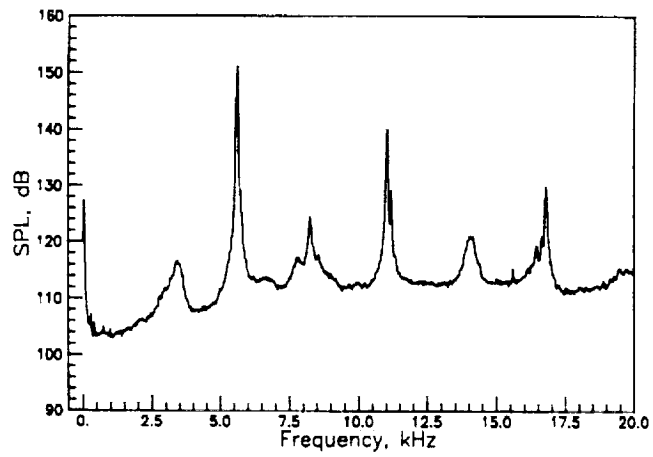


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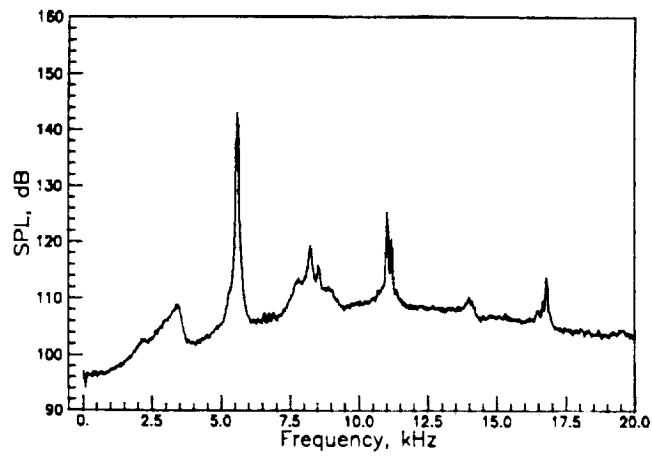
Figure 10. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.19$.



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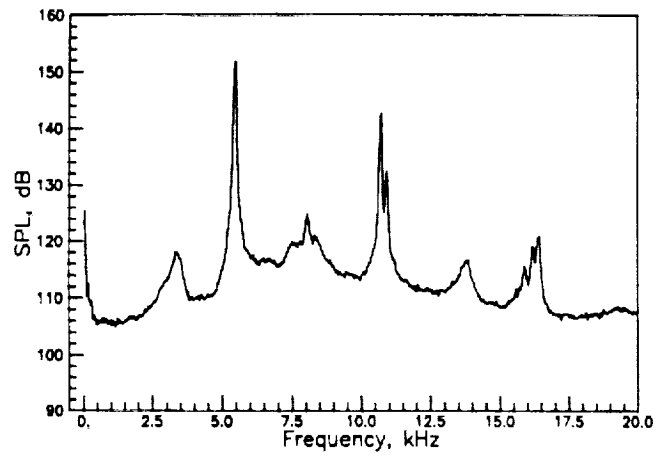


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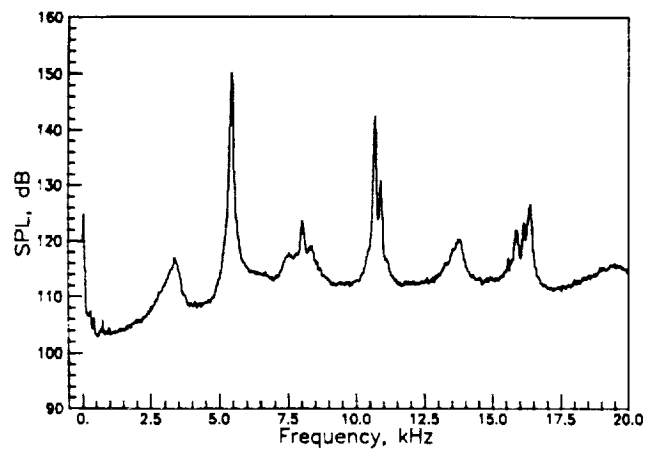


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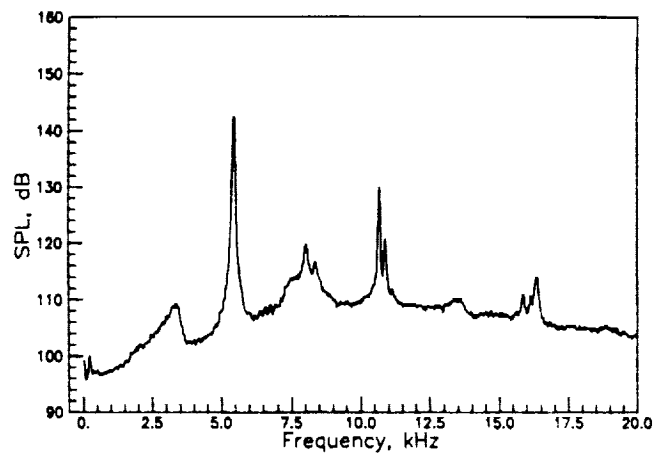
Figure 11. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.21$.



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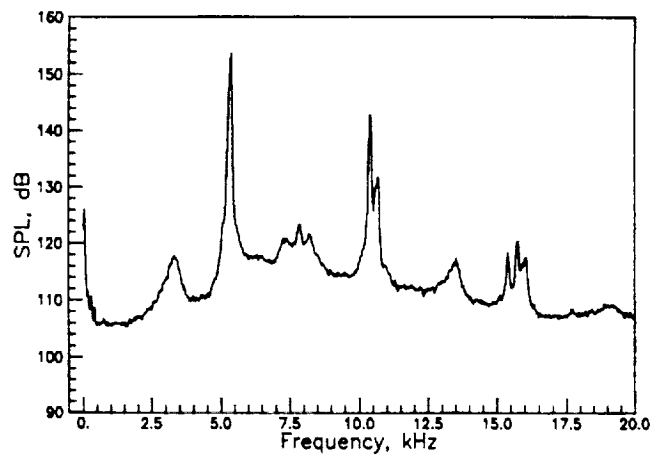


(b) $R/D=0.889$

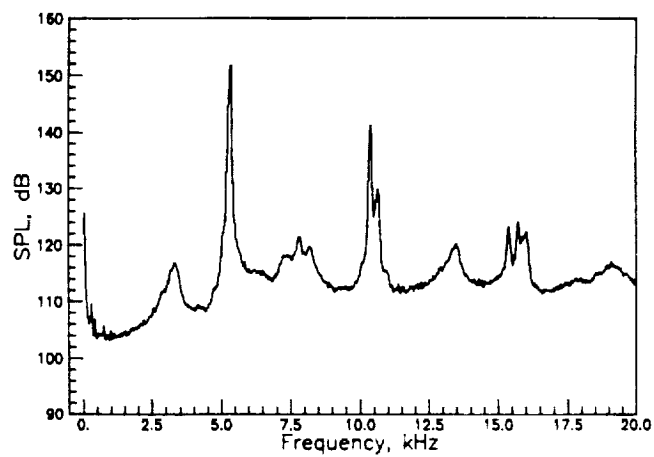


(c) $R/D=2.000$

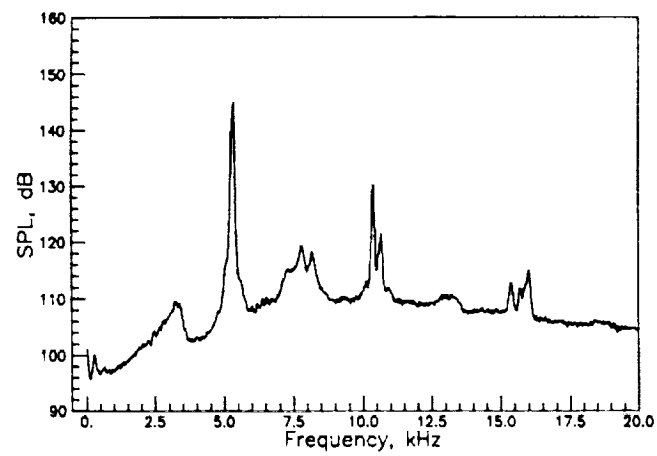
Figure 12. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.23$.



(a) $R/D=0.642$

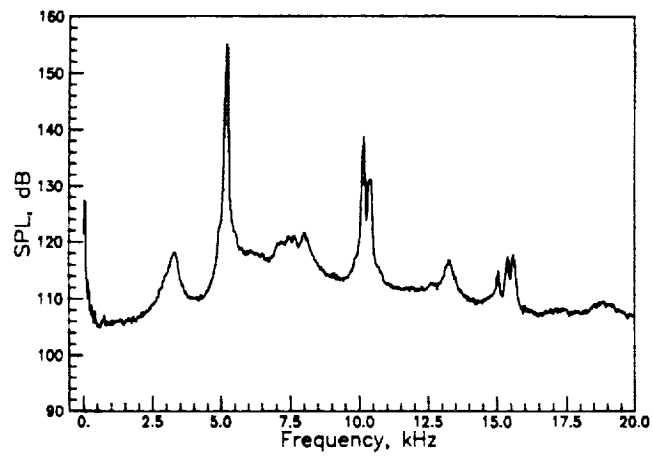


(b) $R/D=0.889$

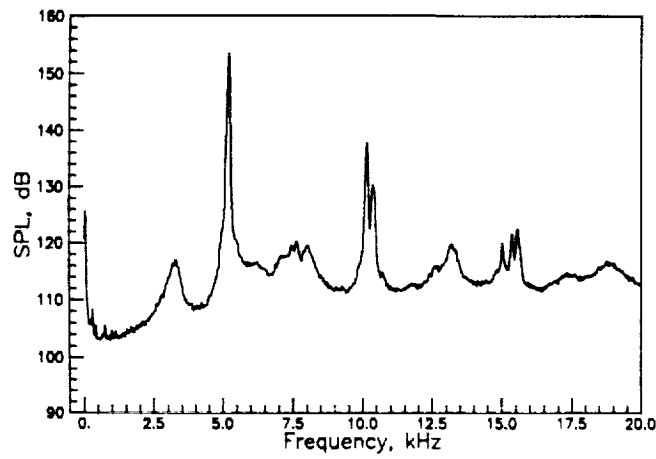


(c) $R/D=2.000$

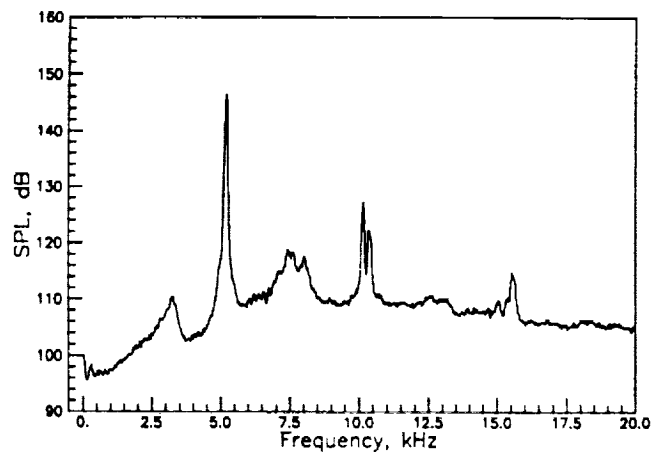
Figure 13. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.25$.



(a) $R/D=0.642$

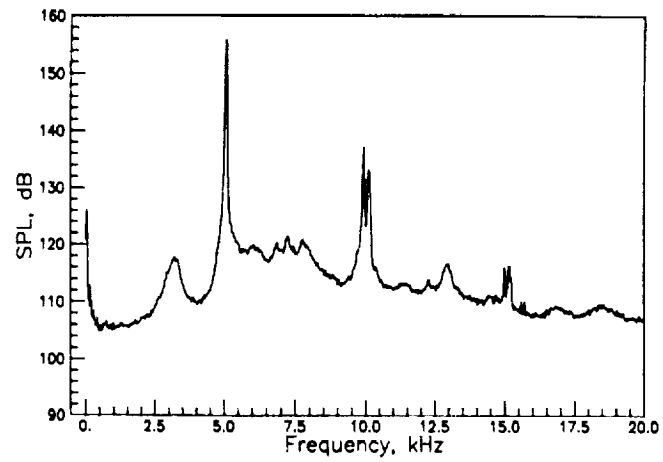


(b) $R/D=0.889$

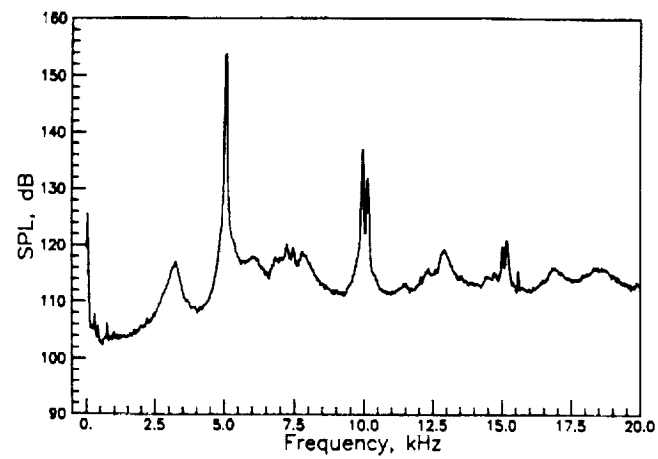


(c) $R/D=2.000$

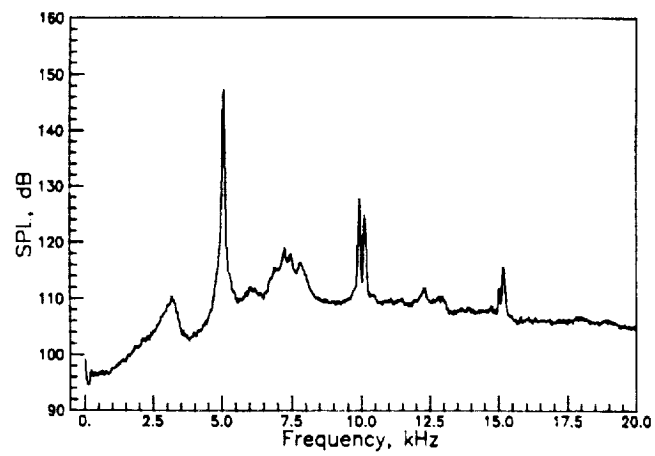
Figure 14. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.27$.



(a) $R/D=0.642$

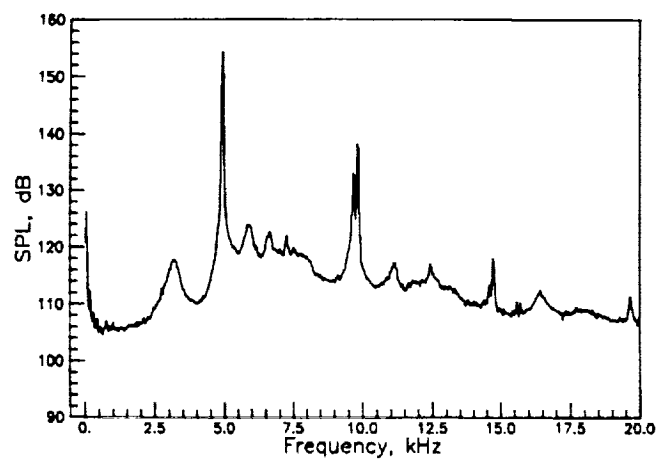


(b) $R/D=0.889$

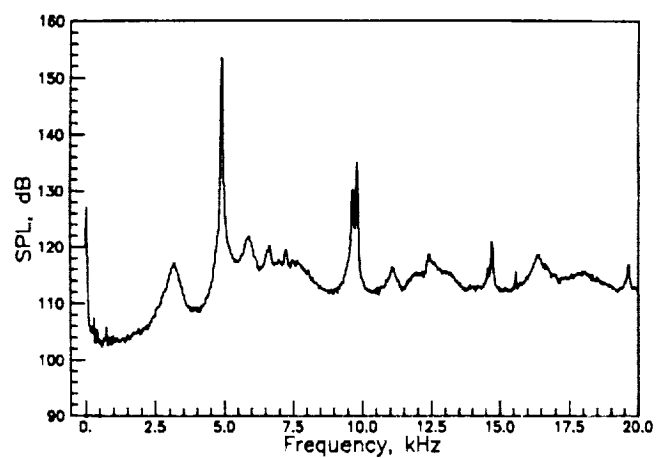


(c) $R/D=2.000$

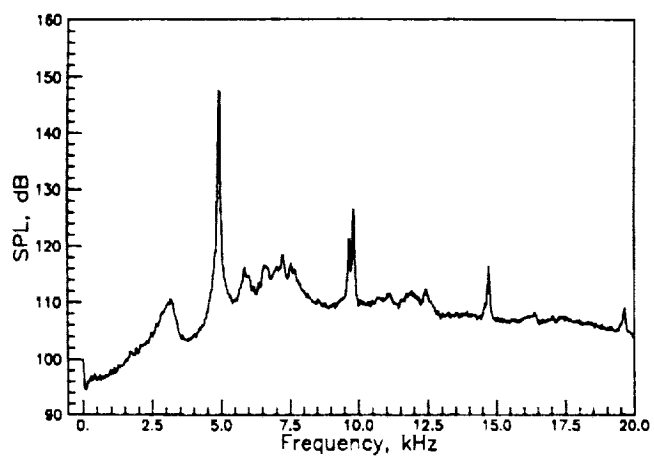
Figure 15. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.29$.



(a) $R/D=0.642$

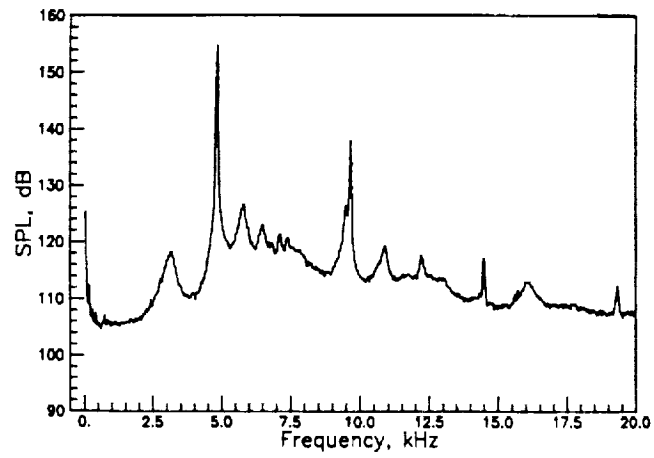


(b) $R/D=0.889$

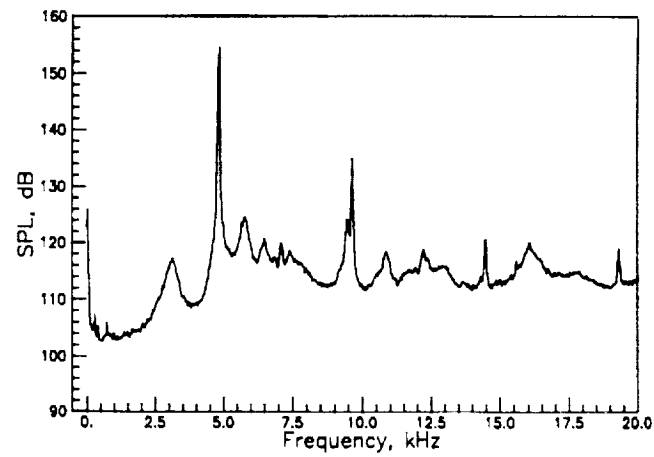


(c) $R/D=2.000$

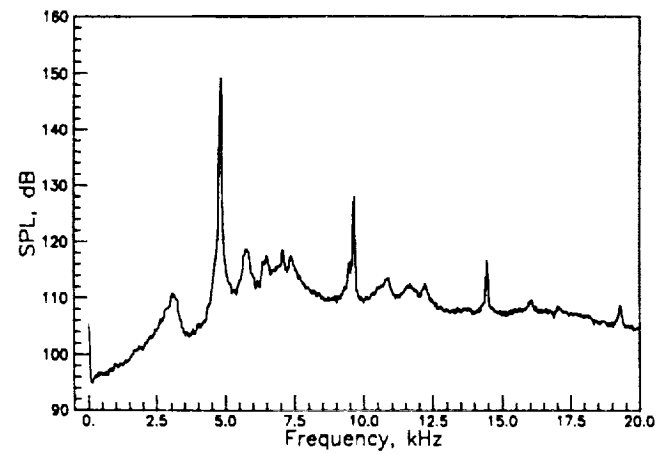
Figure 16. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.31$.



(a) $R/D=0.642$

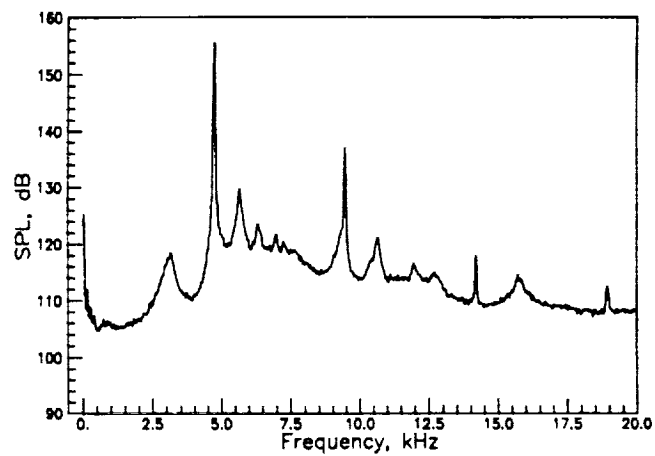


(b) $R/D=0.889$

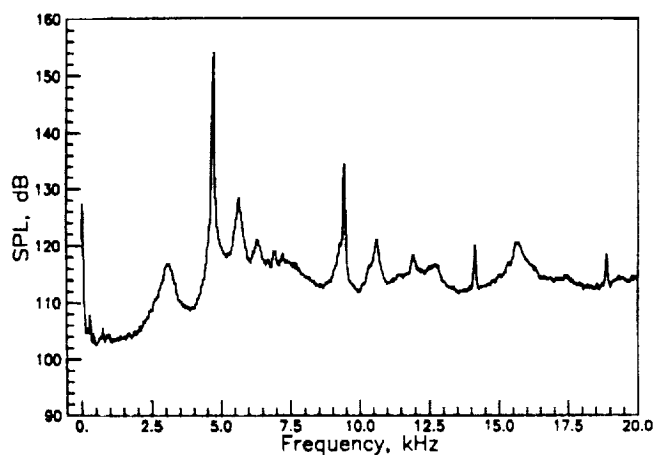


(c) $R/D=2.000$

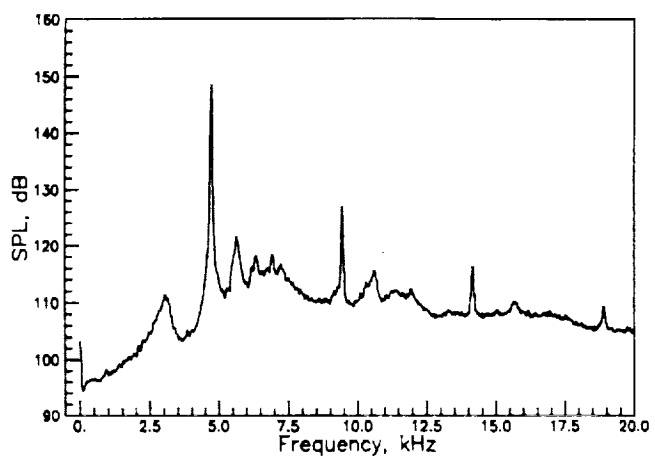
Figure 17. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.33$.



(a) $R/D=0.642$

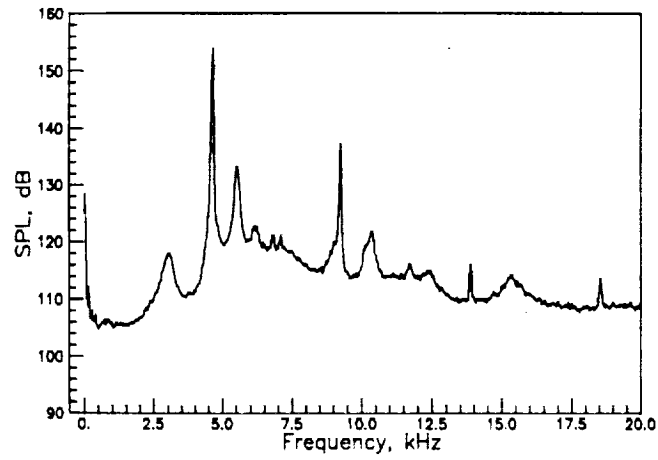


(b) $R/D=0.889$

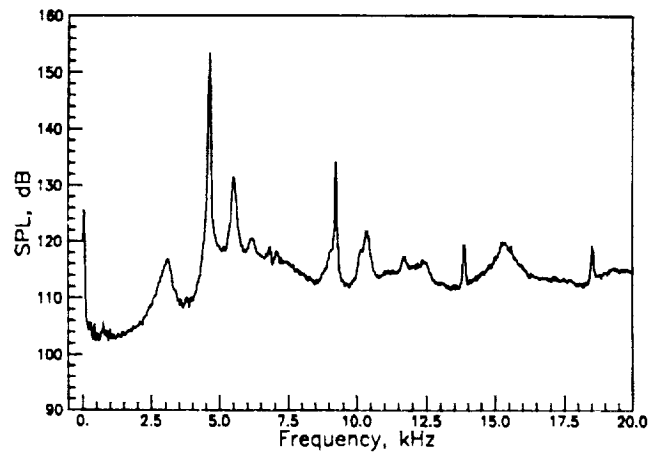


(c) $R/D=2.000$

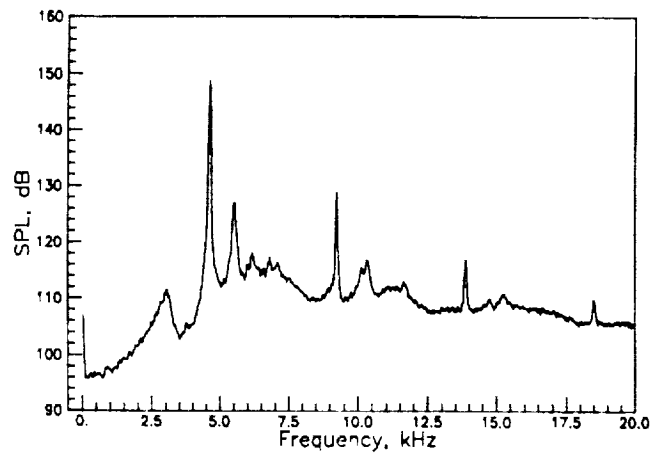
Figure 18. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.35$.



(a) $R/D=0.642$

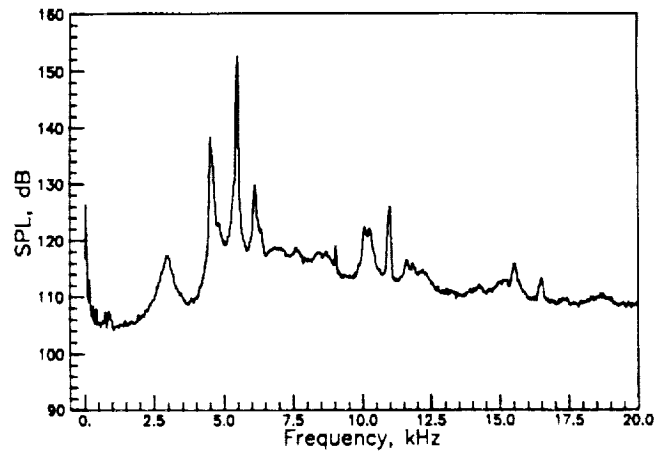


(b) $R/D=0.889$

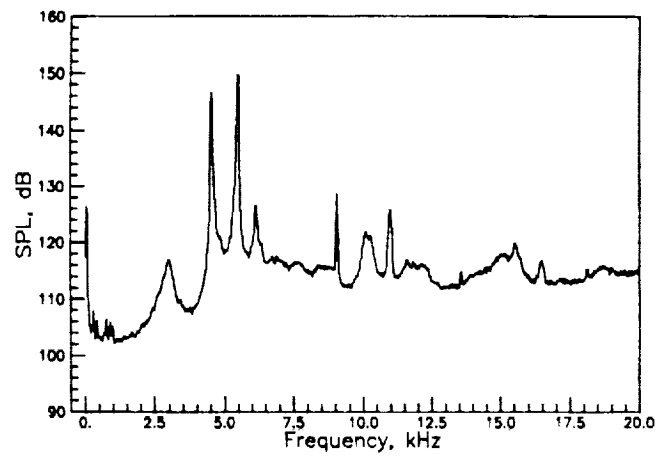


(c) $R/D=2.000$

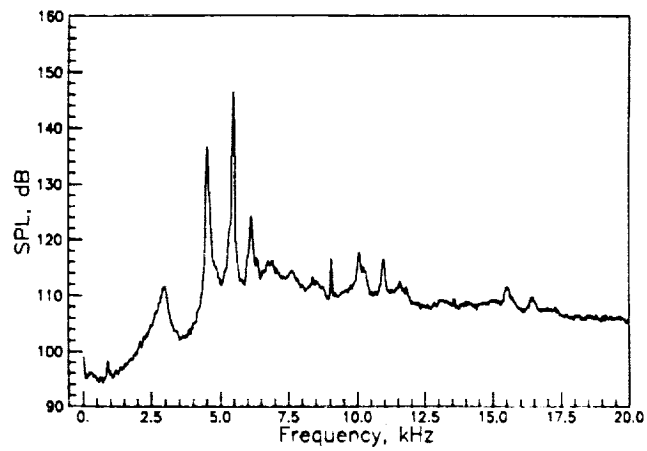
Figure 19. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.37$.



(a) $R/D=0.642$

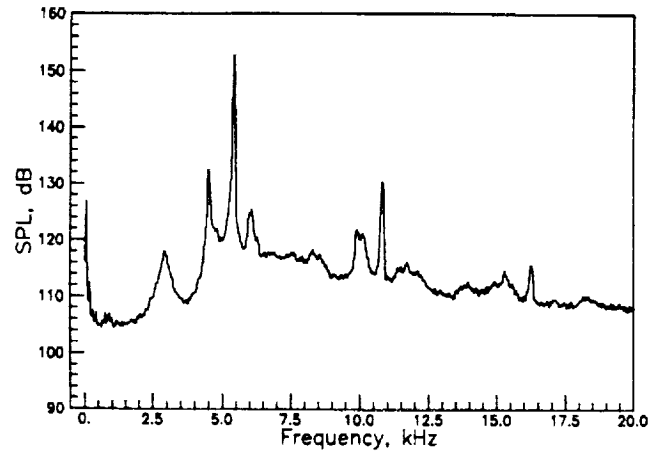


(b) $R/D=0.889$

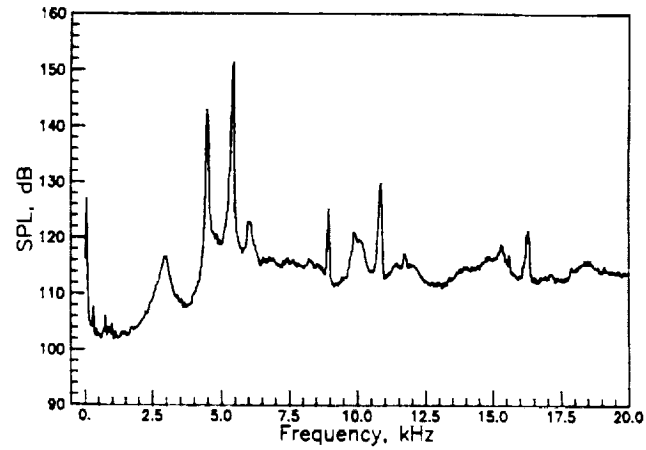


(c) $R/D=2.000$

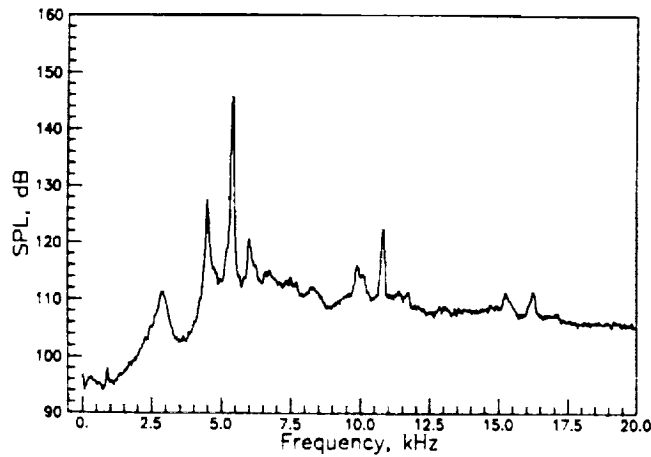
Figure 20. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.39$.



(a) $R/D=0.642$

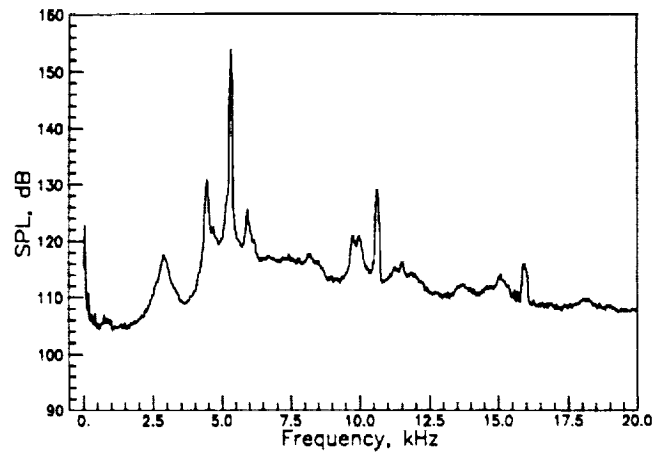


(b) $R/D=0.889$

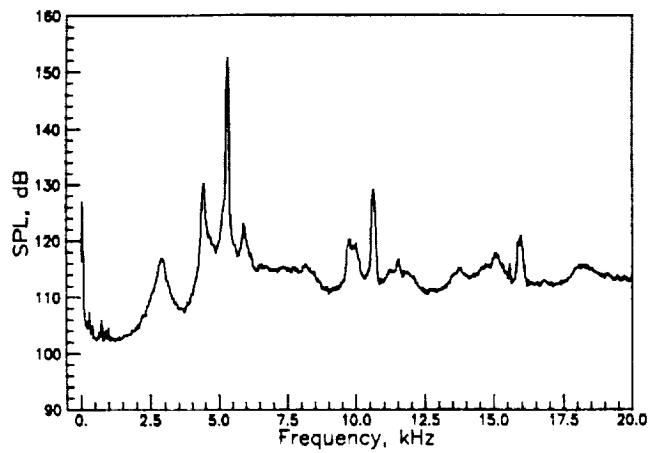


(c) $R/D=2.000$

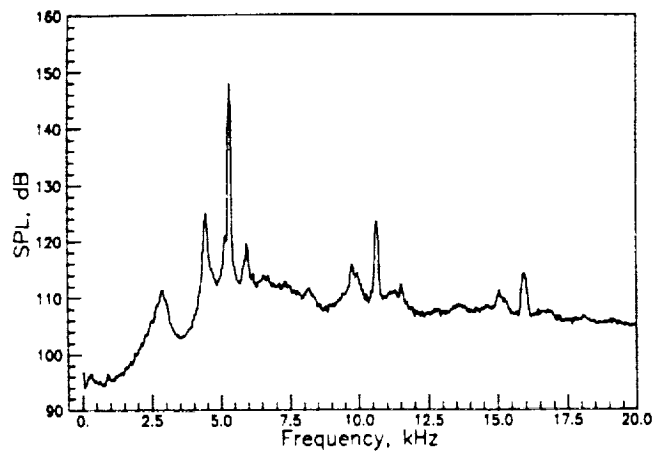
Figure 21. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.41$.



(a) $R/D=0.642$

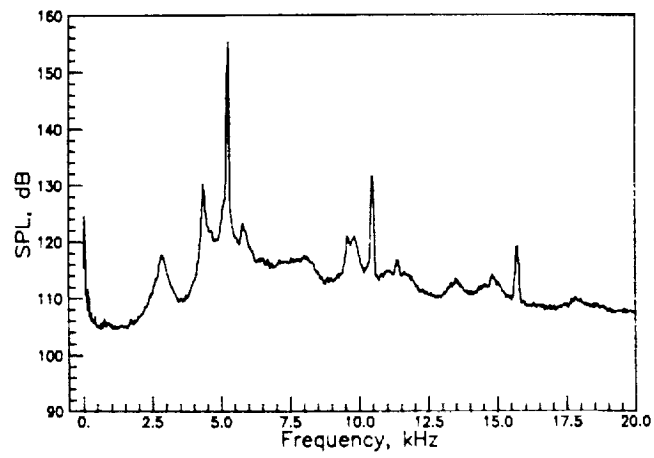


(b) $R/D=0.889$

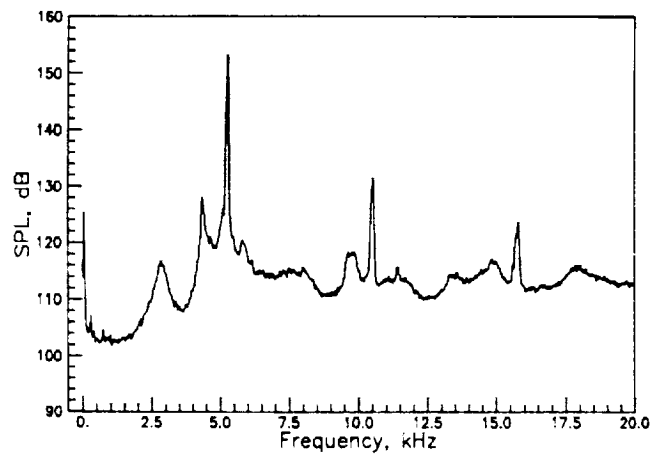


(c) $R/D=2.000$

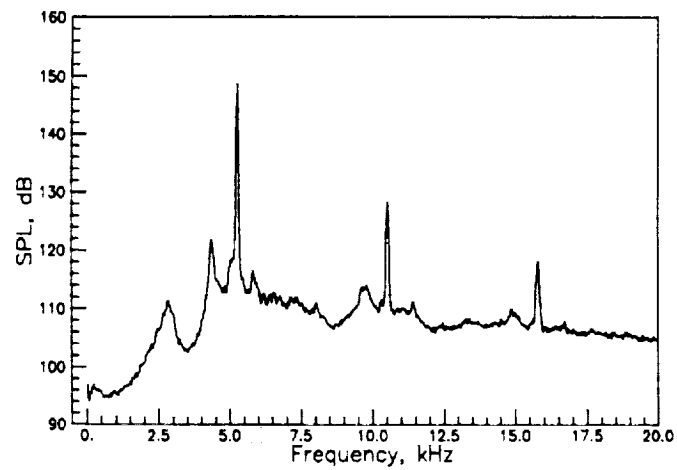
Figure 22. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.42$.



(a) $R/D=0.642$

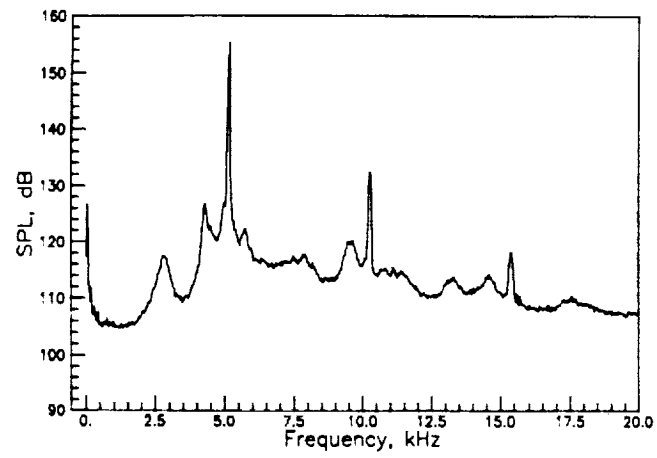


(b) $R/D=0.889$

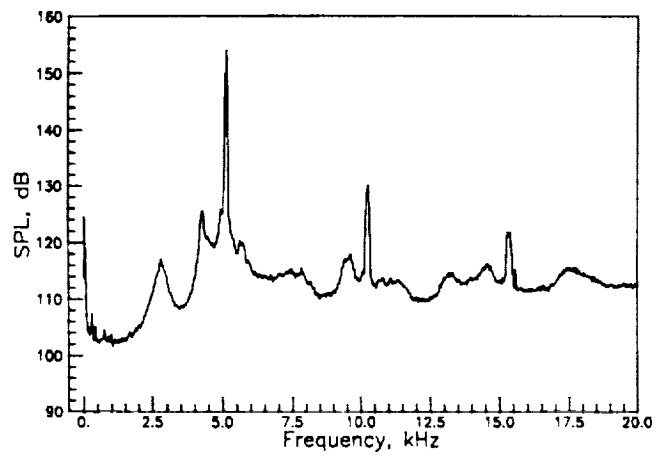


(c) $R/D=2.000$

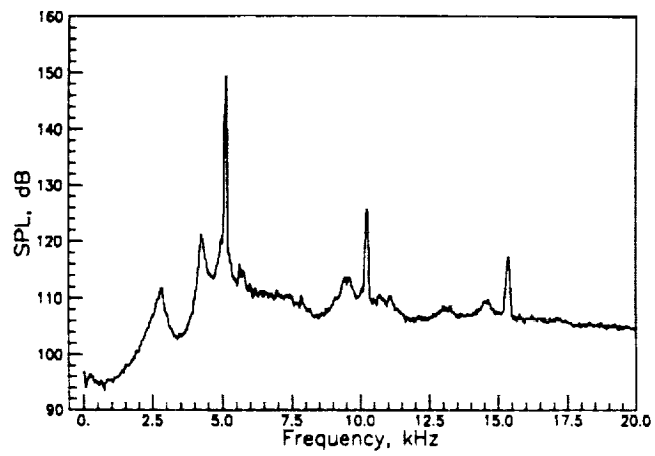
Figure 23. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.44$.



(a) $R/D=0.642$

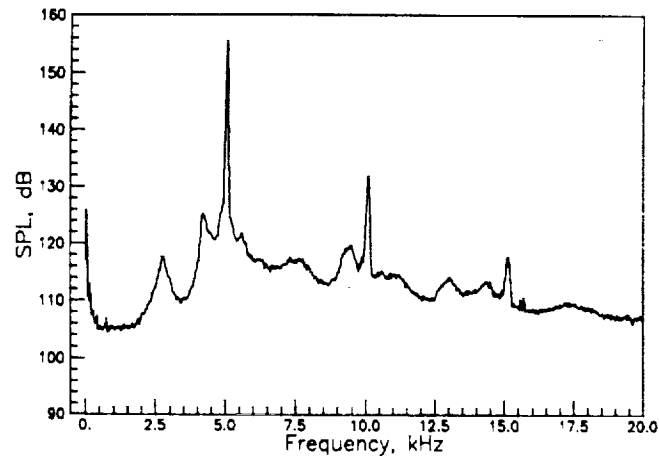


(b) $R/D=0.889$

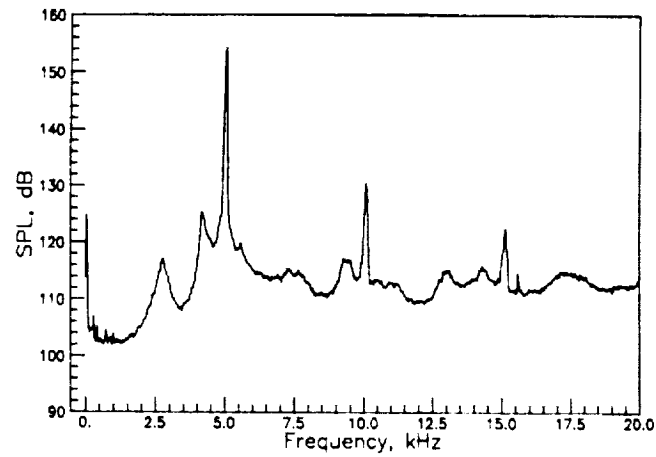


(c) $R/D=2.000$

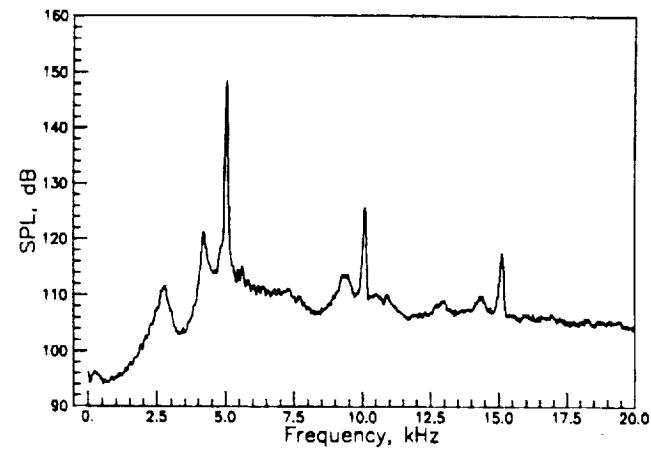
Figure 24. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.46$.



(a) $R/D=0.642$

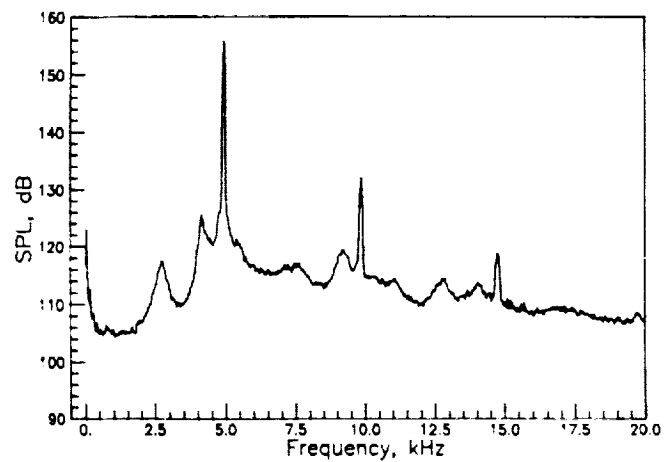


(b) $R/D=0.889$

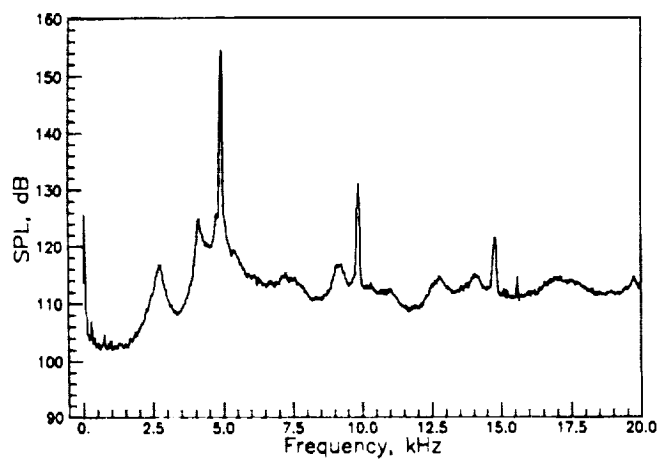


(c) $R/D=2.000$

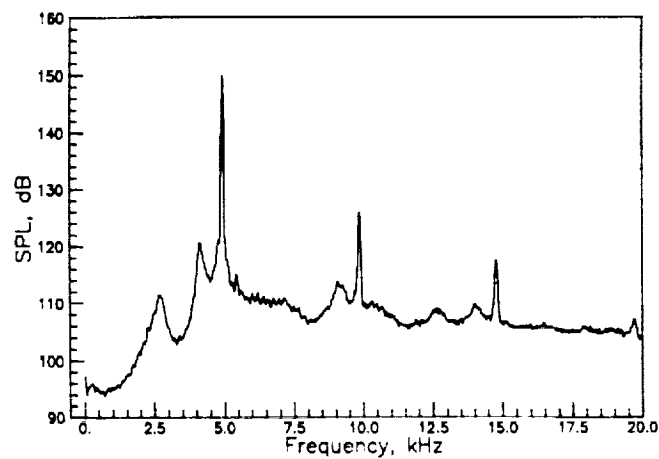
Figure 25. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.48$.



(a) $R/D=0.642$

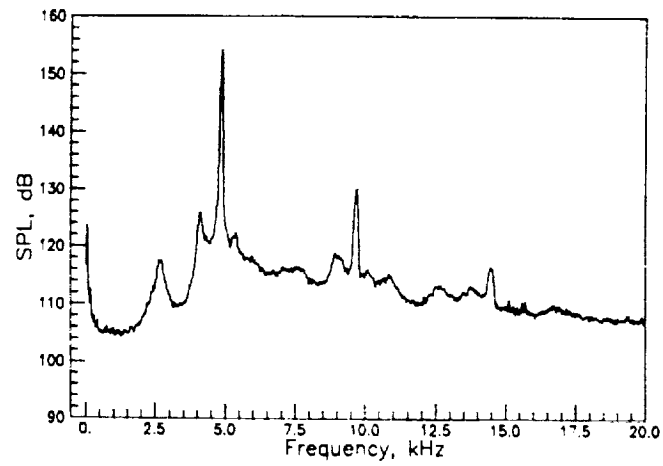


(b) $R/D=0.889$

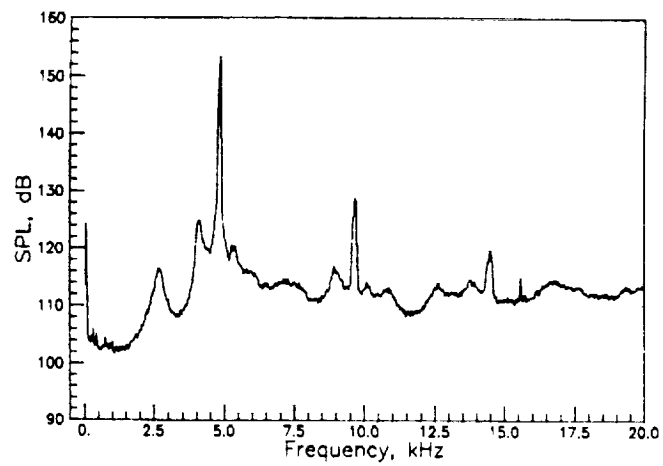


(c) $R/D=2.000$

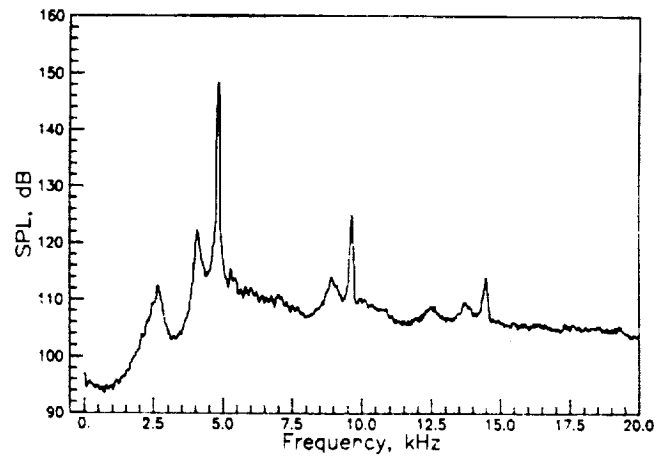
Figure 26. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.50$.



(a) $R/D=0.642$

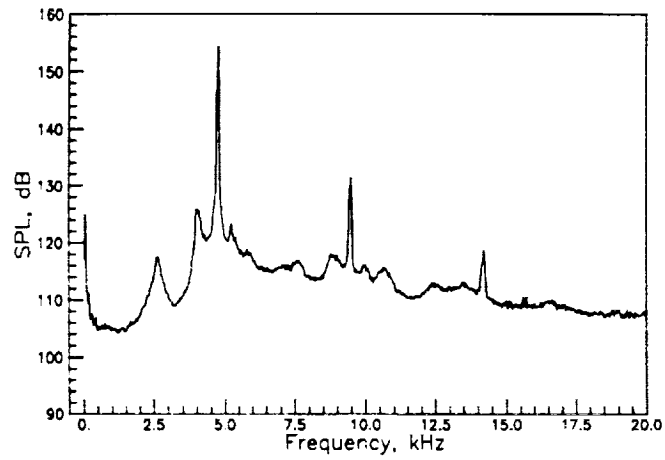


(b) $R/D=0.889$

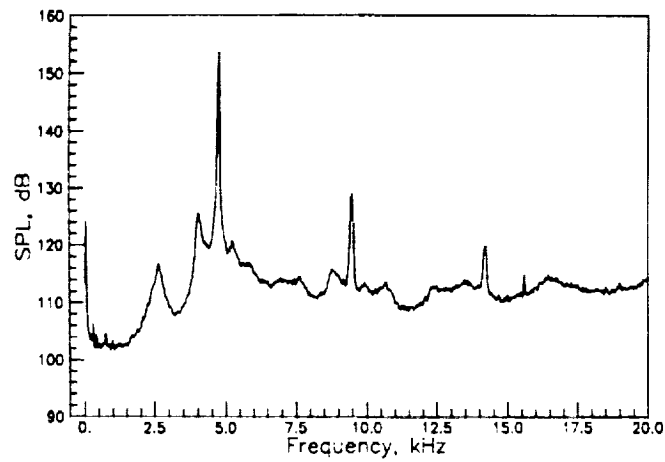


(c) $R/D=2.000$

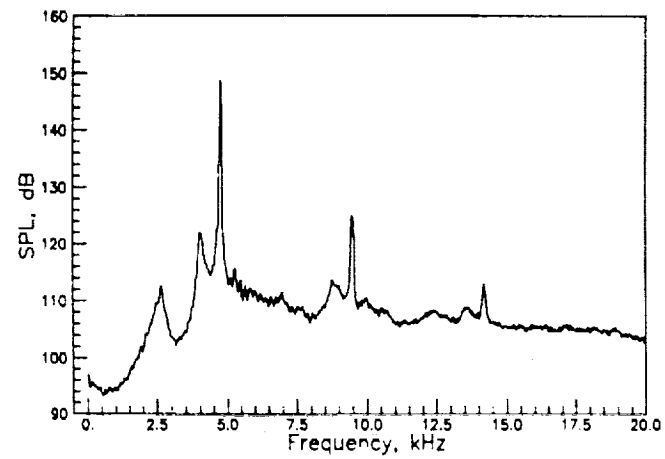
Figure 27. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.52$.



(a) $R/D=0.642$

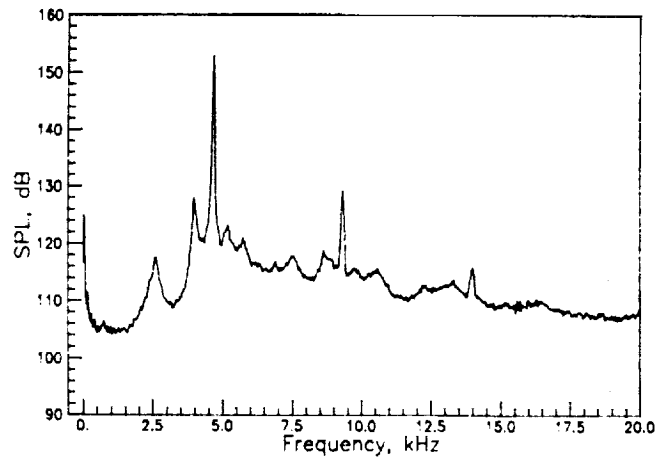


(b) $R/D=0.889$

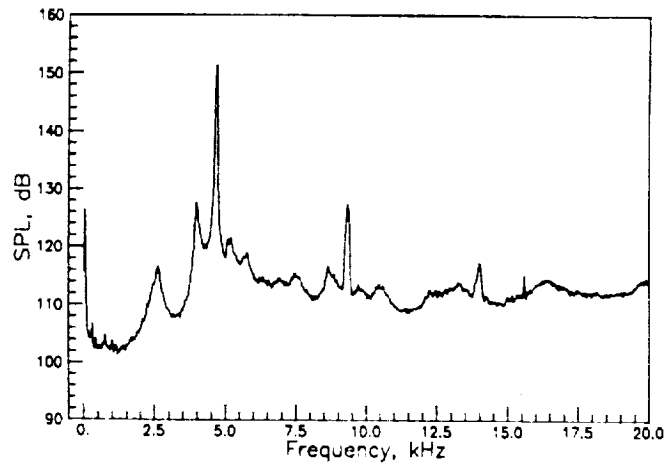


(c) $R/D=2.000$

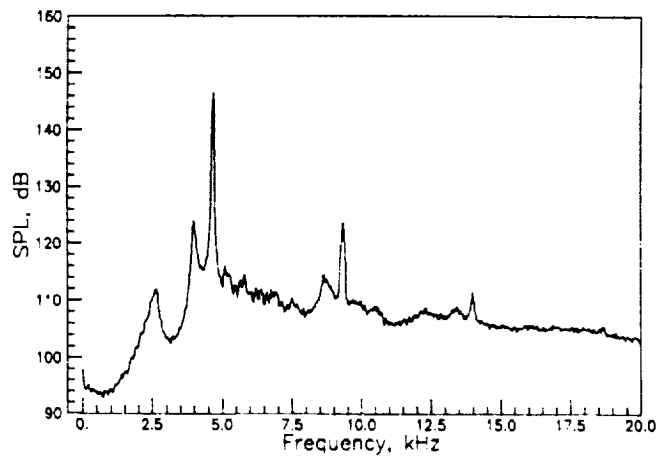
Figure 28. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.54$.



(a) $R/D=0.642$

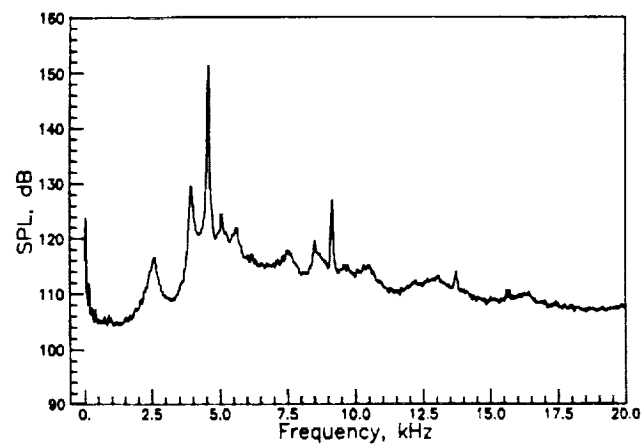


(b) $R/D=0.889$

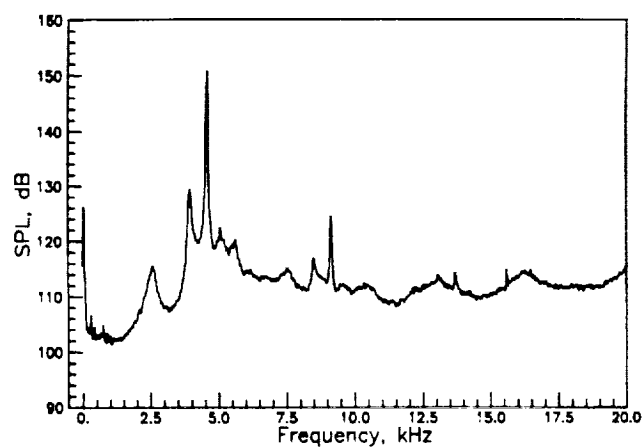


(c) $R/D=2.000$

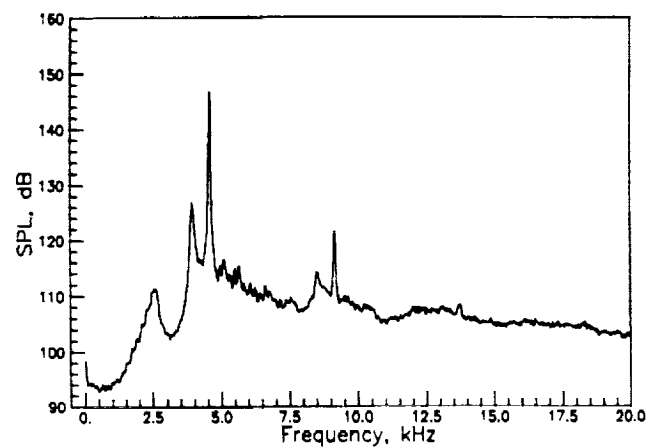
Figure 29. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.56$.



(a) $R/D=0.642$

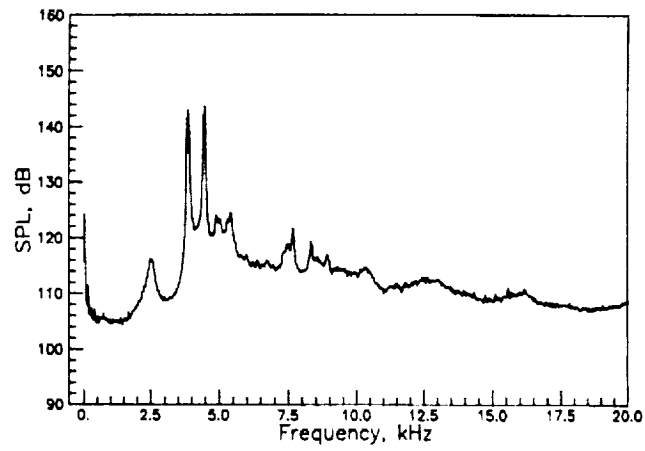


(b) $R/D=0.889$

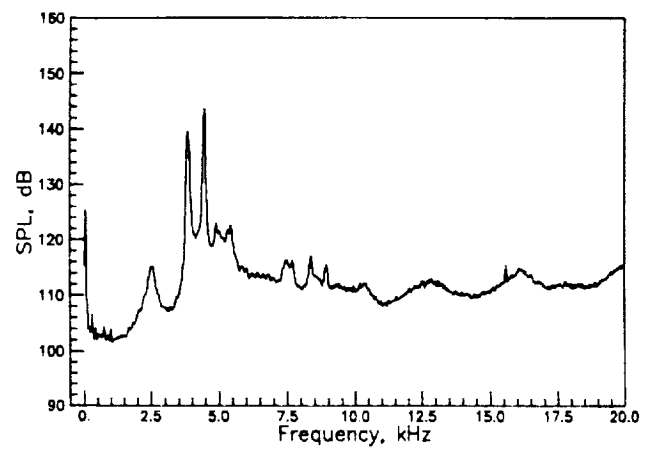


(c) $R/D=2.000$

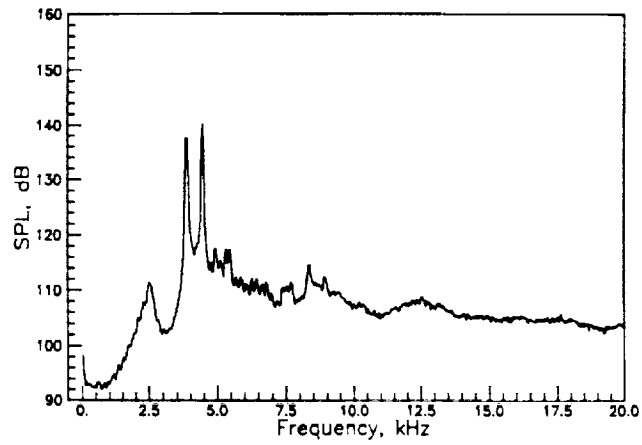
Figure 30. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.58$.



(a) $R/D=0.642$

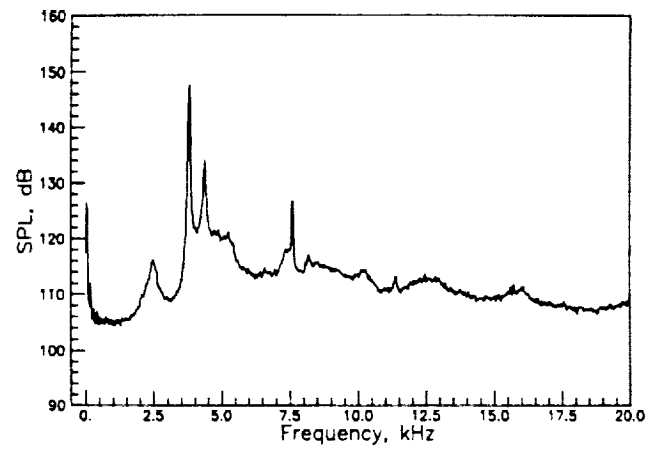


(b) $R/D=0.889$

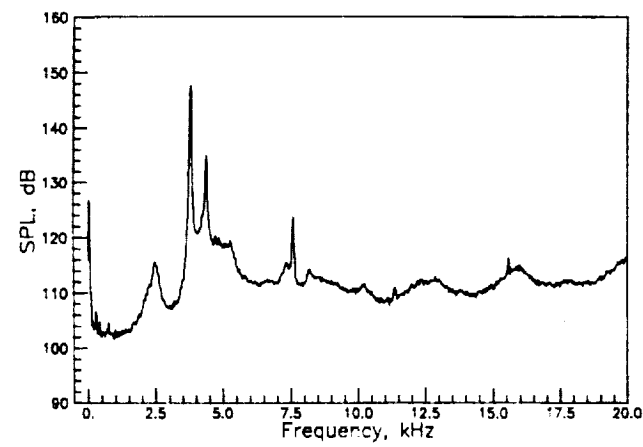


(c) $R/D=2.000$

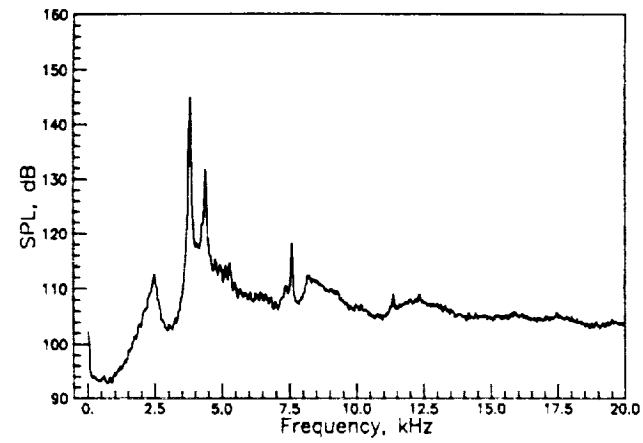
Figure 31. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.60$.



(a) $R/D=0.642$

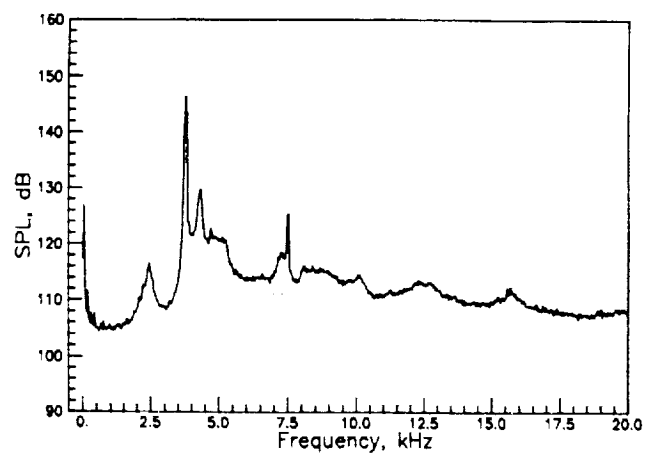


(b) $R/D=0.889$

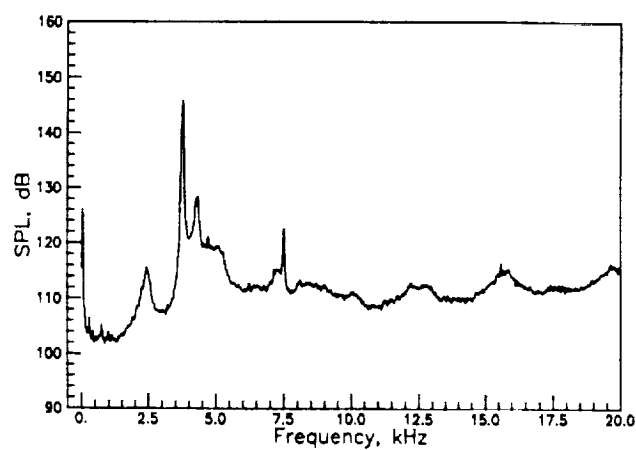


(c) $R/D=2.000$

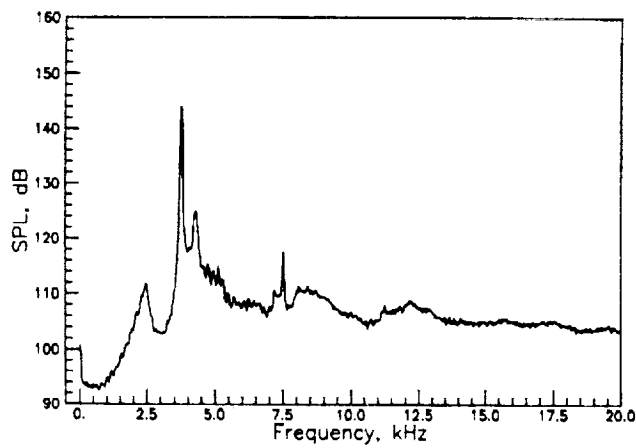
Figure 32. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.62$.



(a) $R/D=0.642$

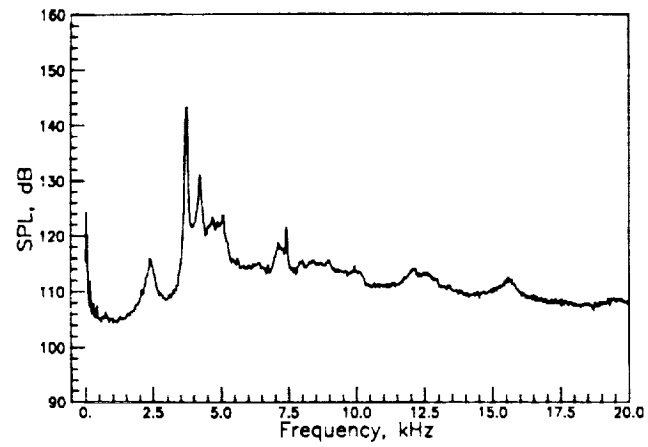


(b) $R/D=0.889$

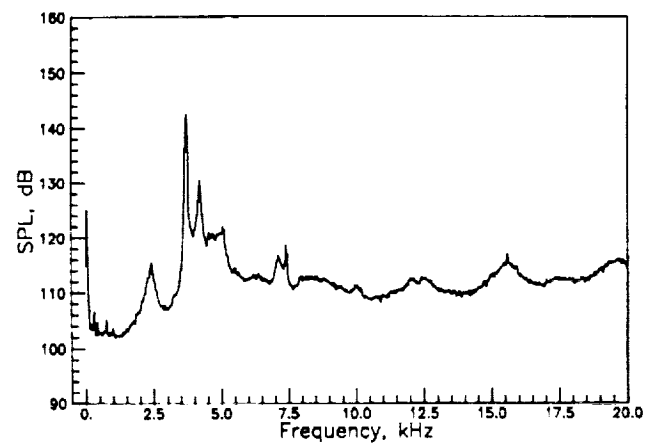


(c) $R/D=2.000$

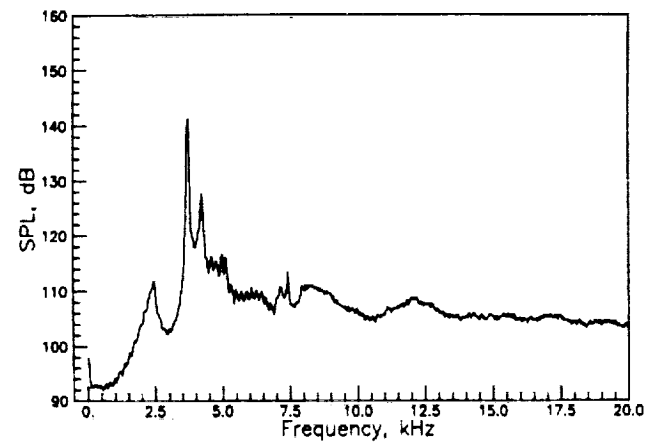
Figure 33. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.64$.



(a) $R/D=0.642$

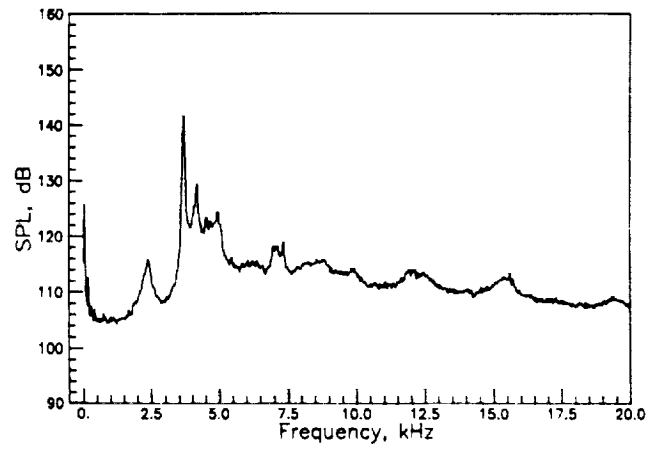


(b) $R/D=0.889$

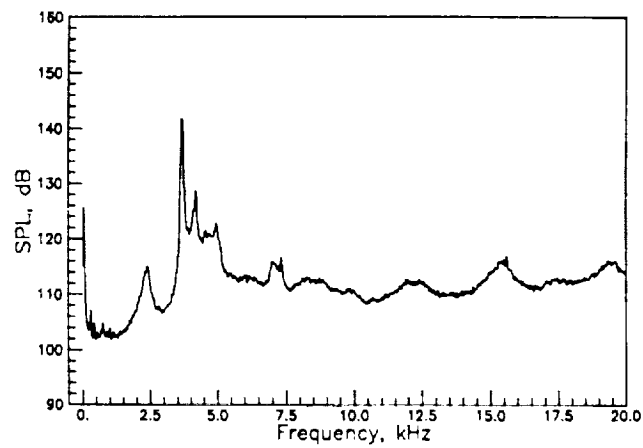


(c) $R/D=2.000$

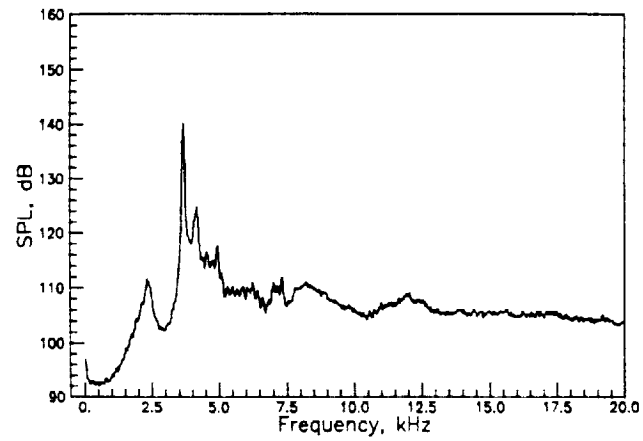
Figure 34. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.66$.



(a) $R/D=0.642$

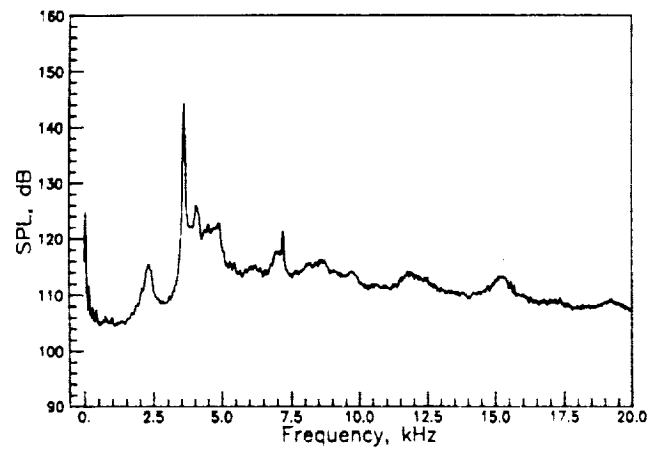


(b) $R/D=0.889$

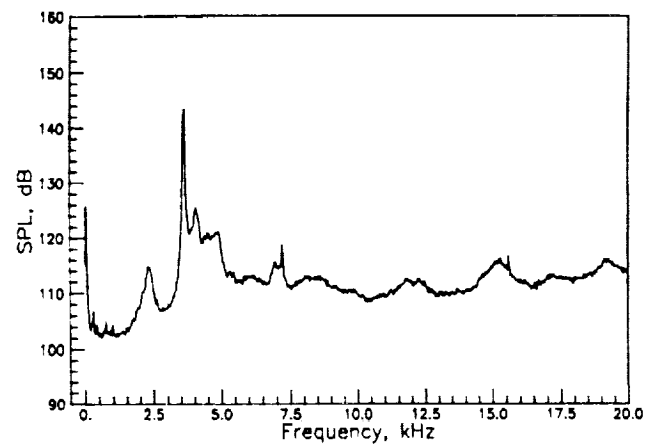


(c) $R/D=2.000$

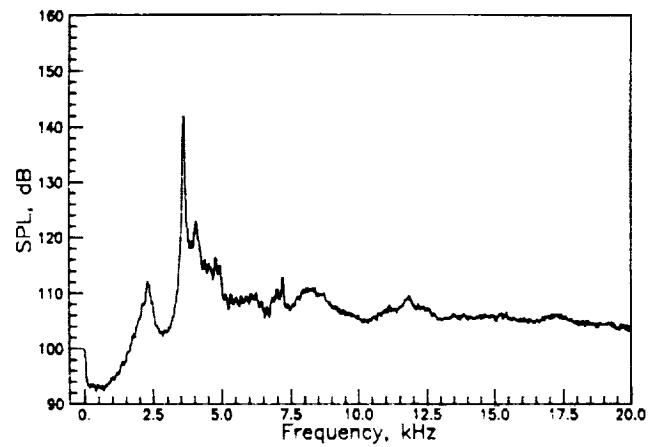
Figure 35. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.68$.



(a) $R/D=0.642$

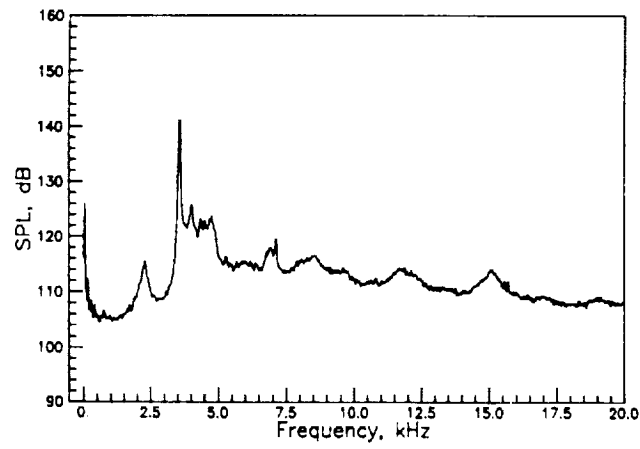


(b) $R/D=0.889$

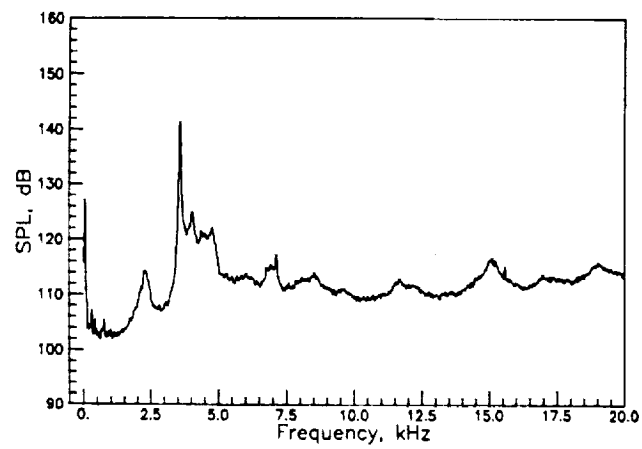


(c) $R/D=2.000$

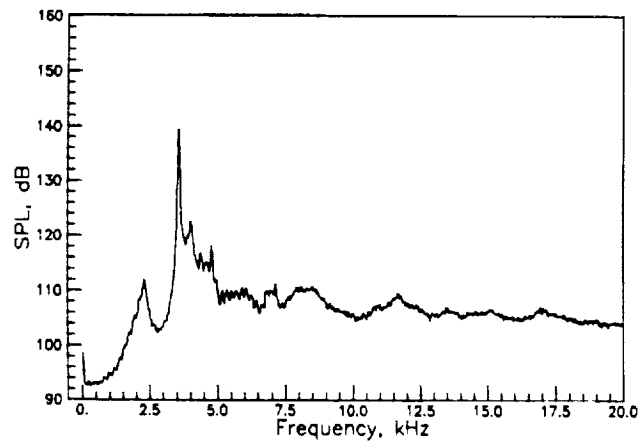
Figure 36. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.70$.



(a) $R/D=0.642$

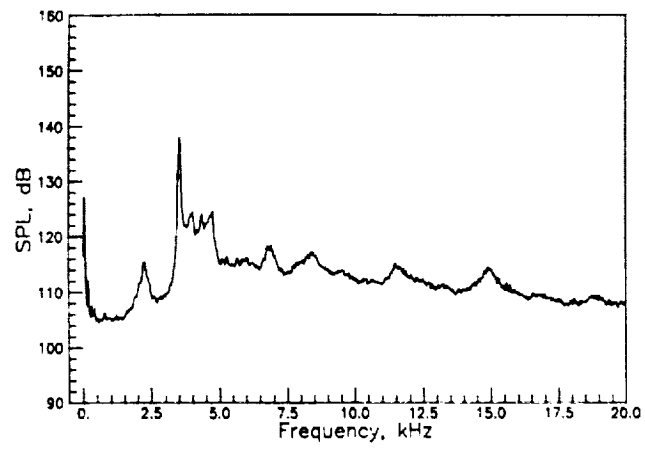


(b) $R/D=0.889$

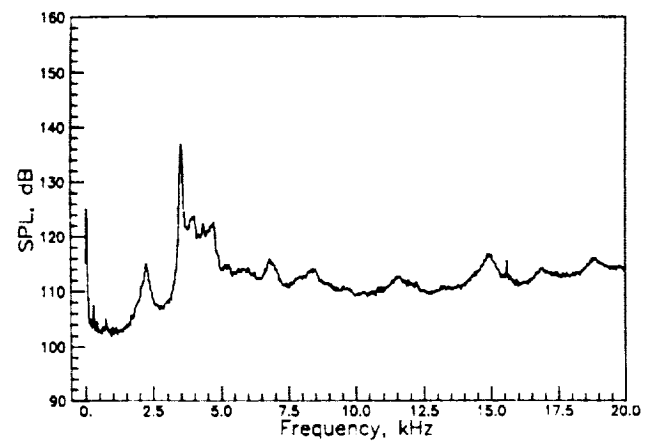


(c) $R/D=2.000$

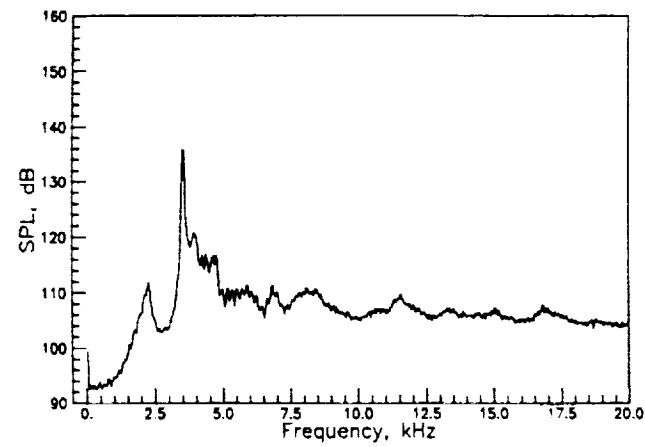
Figure 37. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.72$.



(a) $R/D=0.642$

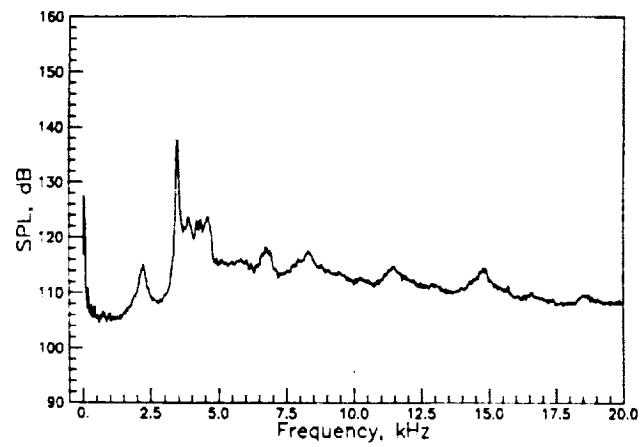


(b) $R/D=0.889$

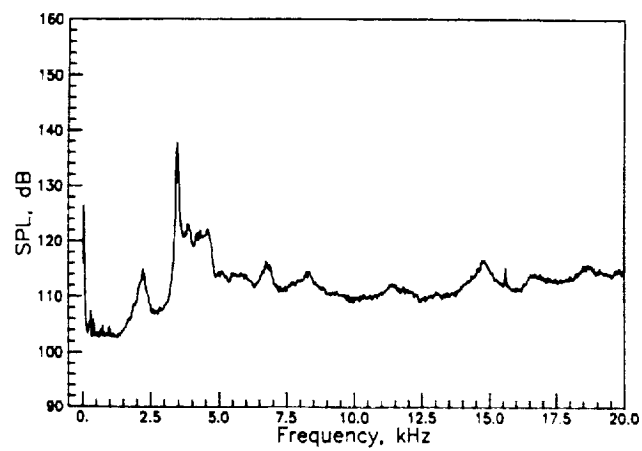


(c) $R/D=2.000$

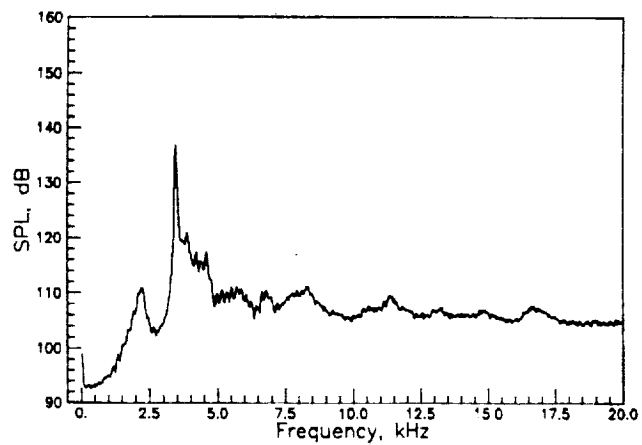
Figure 38. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.74$.



(a) $R/D=0.642$

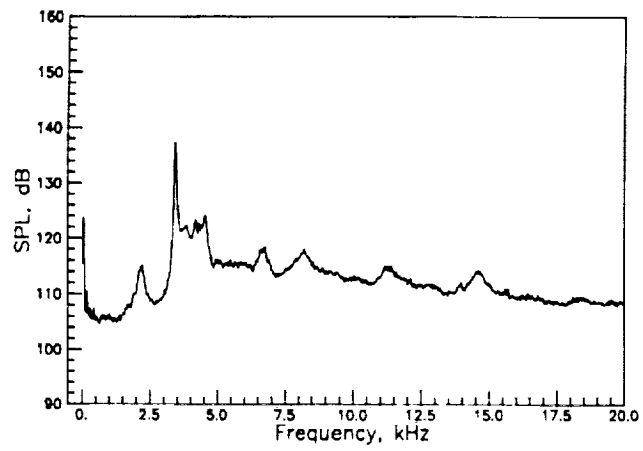


(b) $R/D=0.889$

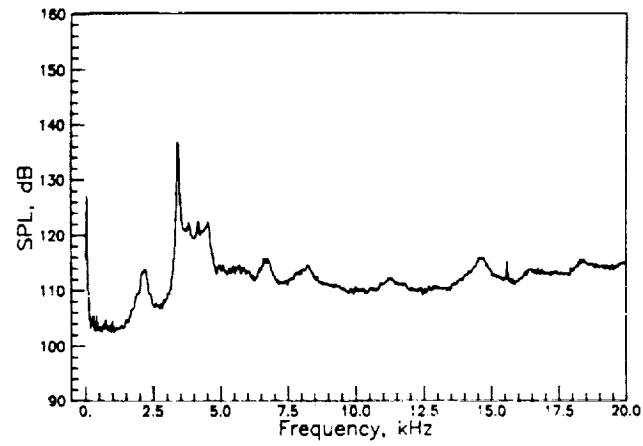


(c) $R/D=2.000$

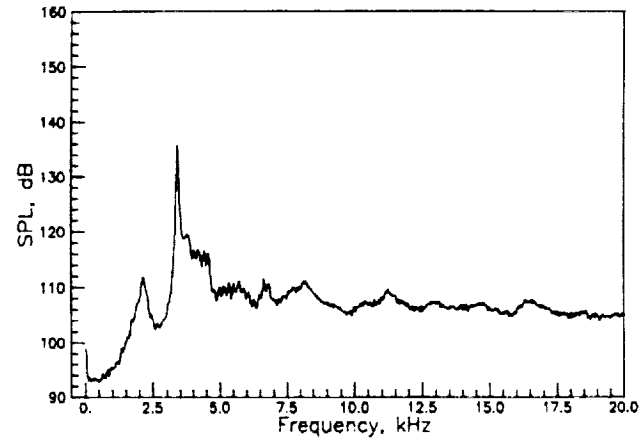
Figure 39. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.76$.



(a) $R/D=0.642$

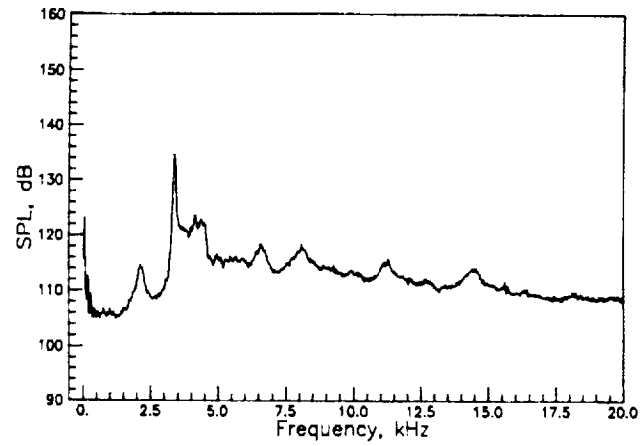


(b) $R/D=0.889$

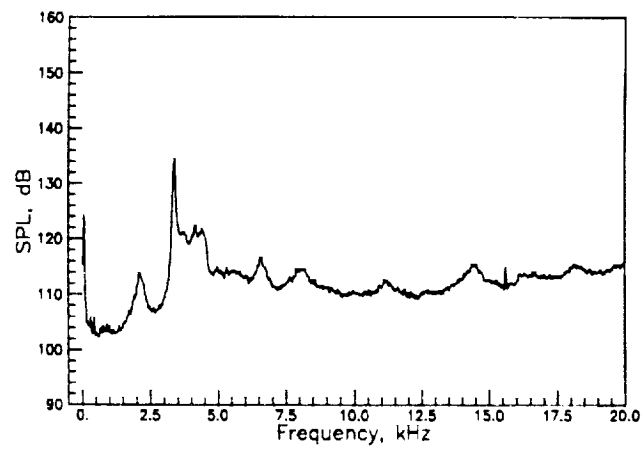


(c) $R/D=2.000$

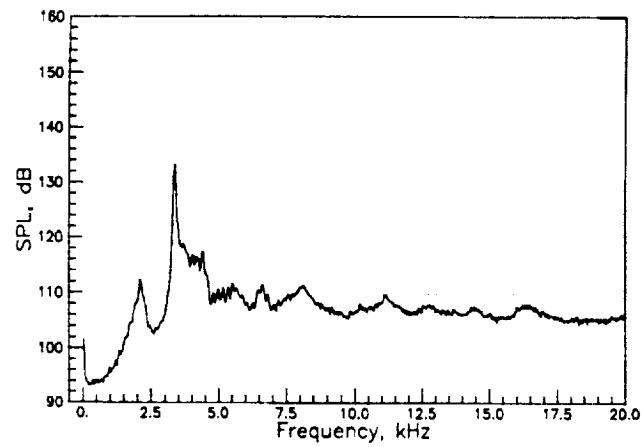
Figure 40. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.78$.



(a) $R/D=0.642$

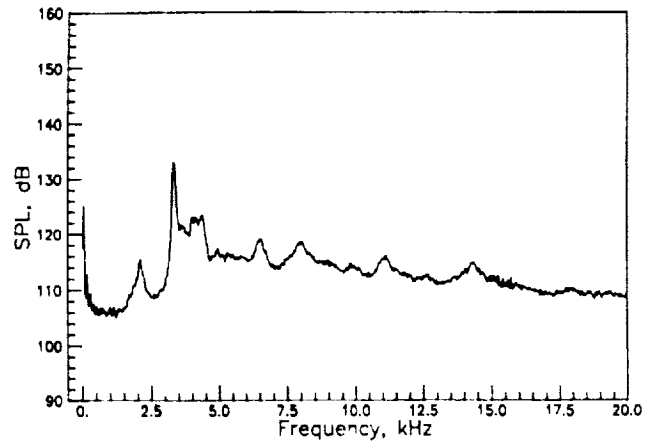


(b) $R/D=0.889$

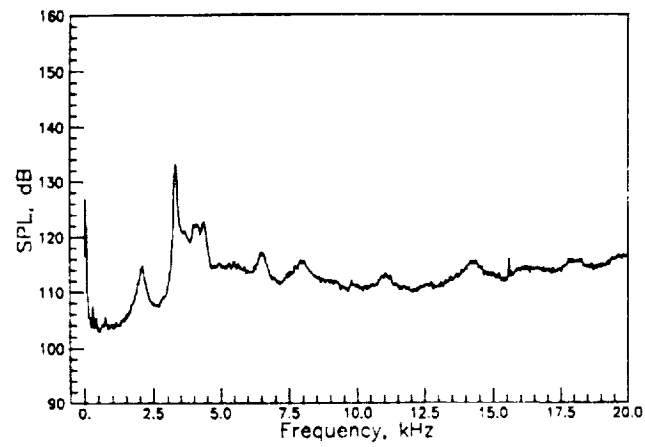


(c) $R/D=2.000$

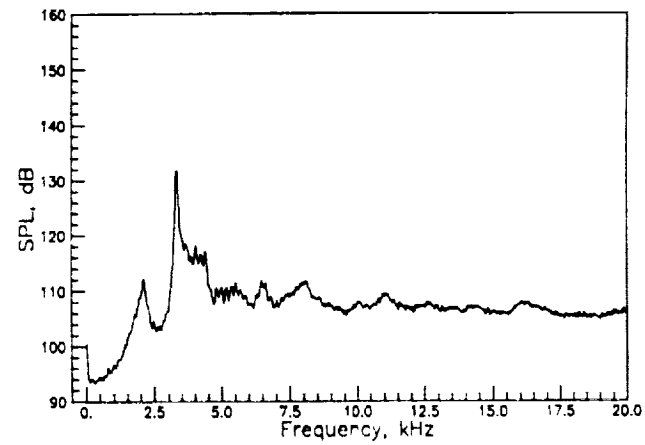
Figure 41. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.80$.



(a) $R/D=0.642$

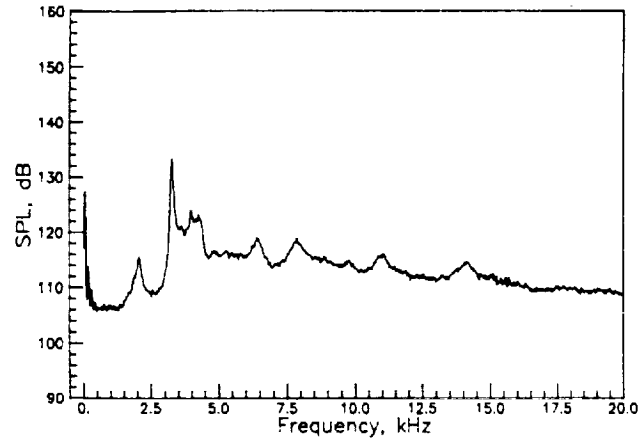


(b) $R/D=0.889$

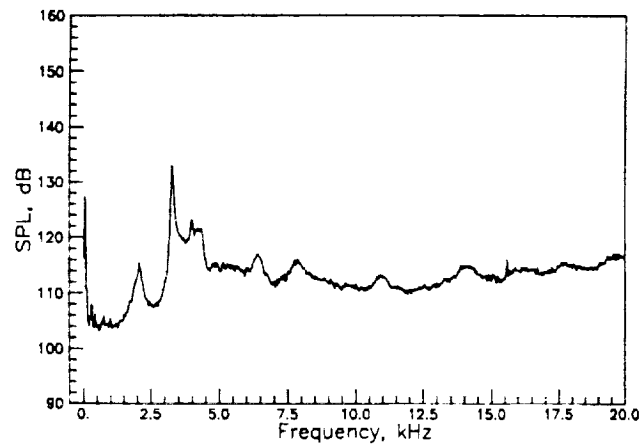


(c) $R/D=2.000$

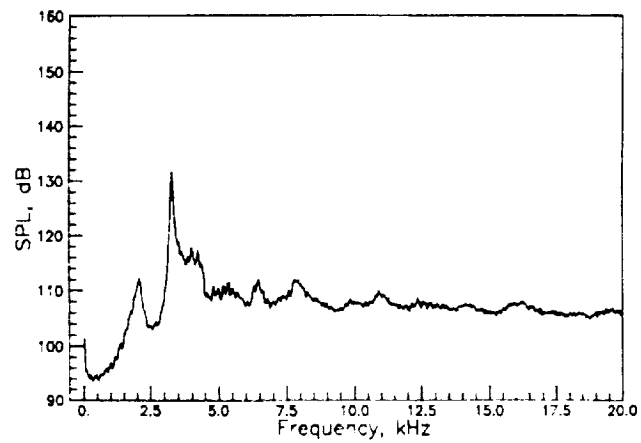
Figure 42. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.82$.



(a) $R/D=0.642$

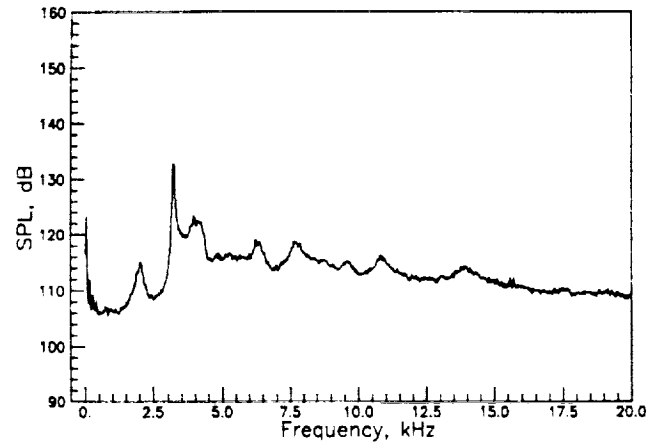


(b) $R/D=0.889$

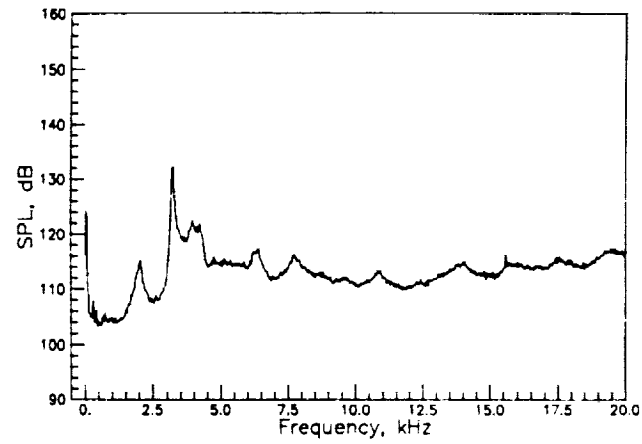


(c) $R/D=2.000$

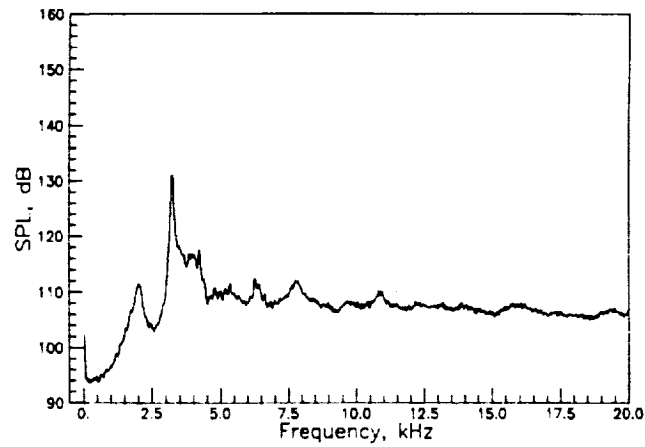
Figure 43. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.84$.



(a) $R/D=0.642$

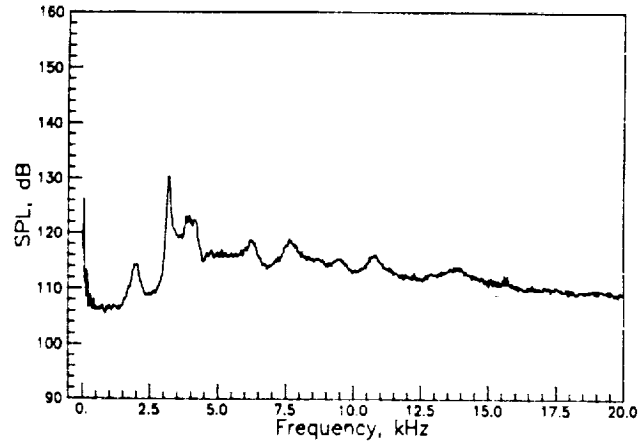


(b) $R/D=0.889$

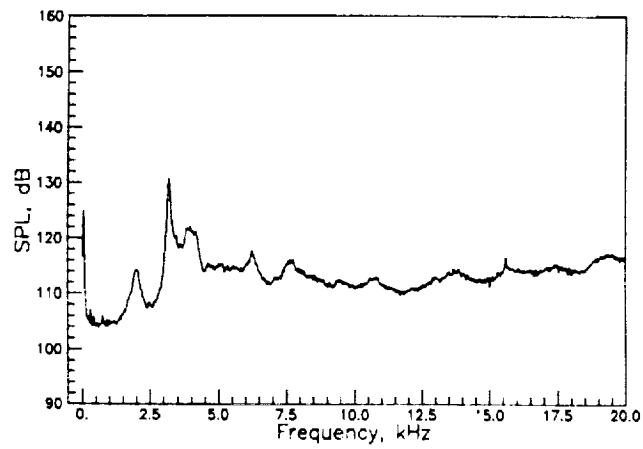


(c) $R/D=2.000$

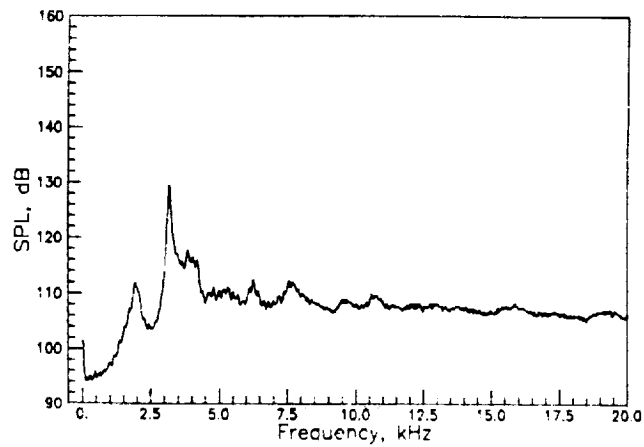
Figure 44. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.86$.



(a) $R/D=0.642$

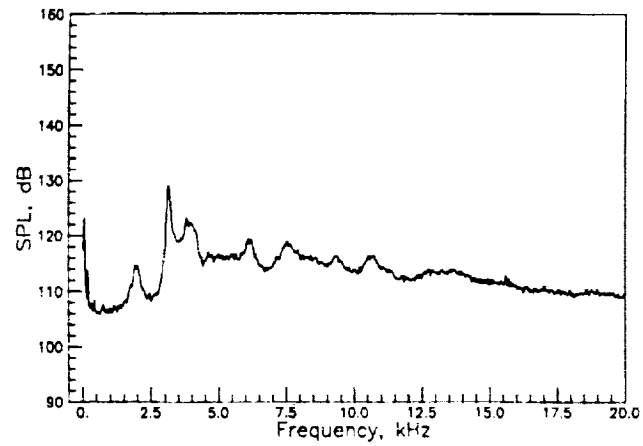


(b) $R/D=0.889$

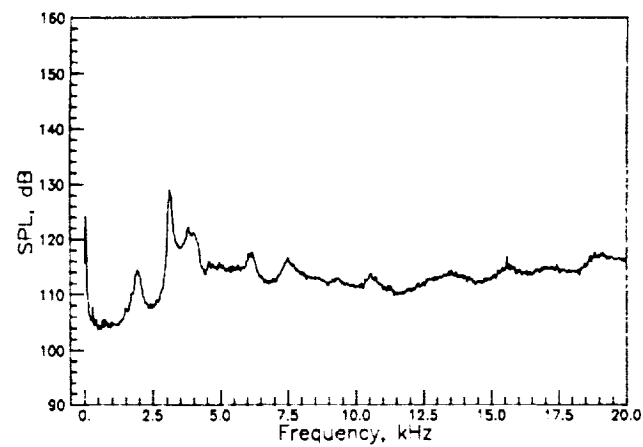


(c) $R/D=2.000$

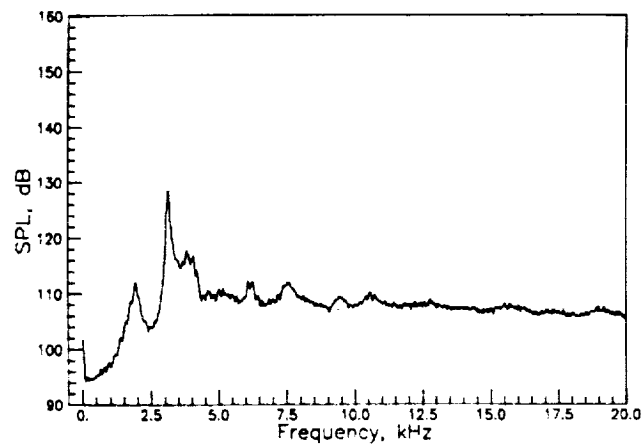
Figure 45. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.88$.



(a) $R/D=0.642$

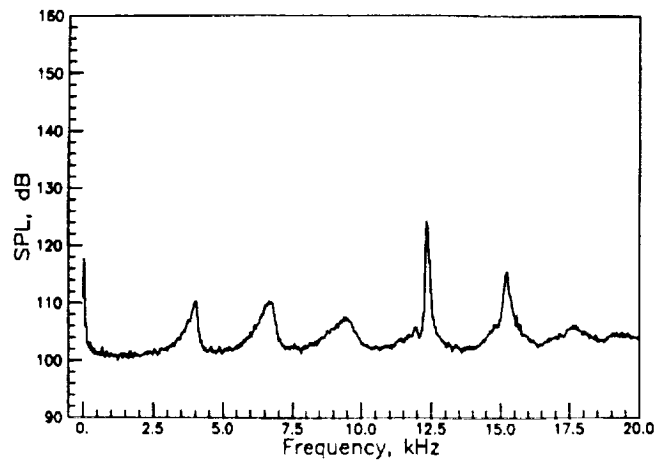


(b) $R/D=0.889$

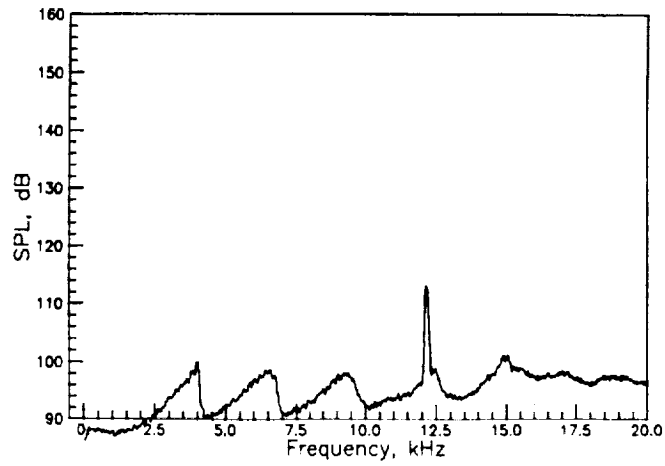


(c) $R/D=2.000$

Figure 46. Narrowband spectra for the 0.625 inch lip thickness nozzle at $M_j=1.90$.

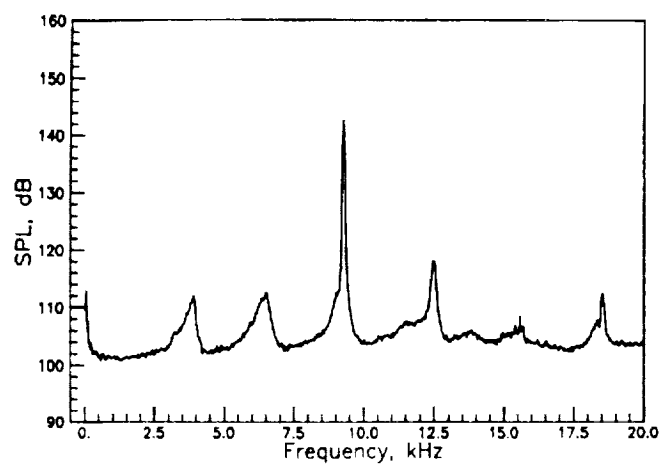


(a) $R/D=0.642$

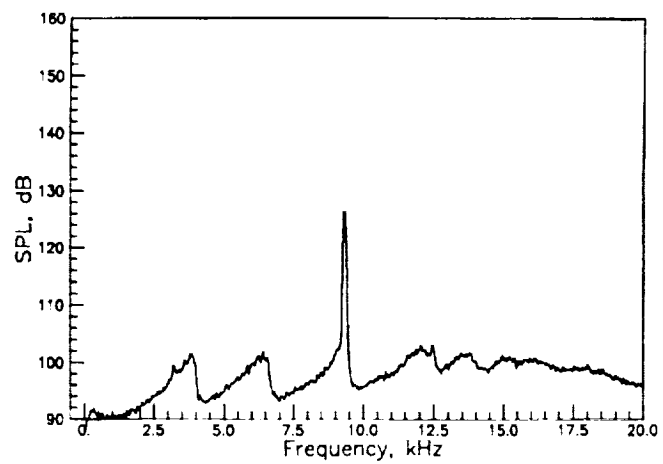


(b) $R/D=2.000$

Figure 47. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.04$.

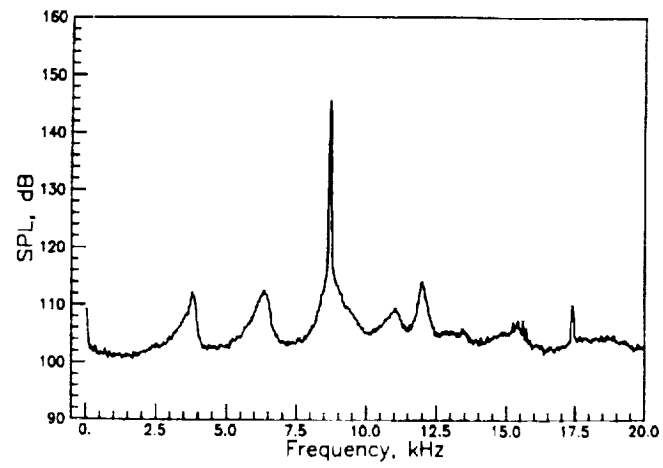


(a) $R/D=0.642$

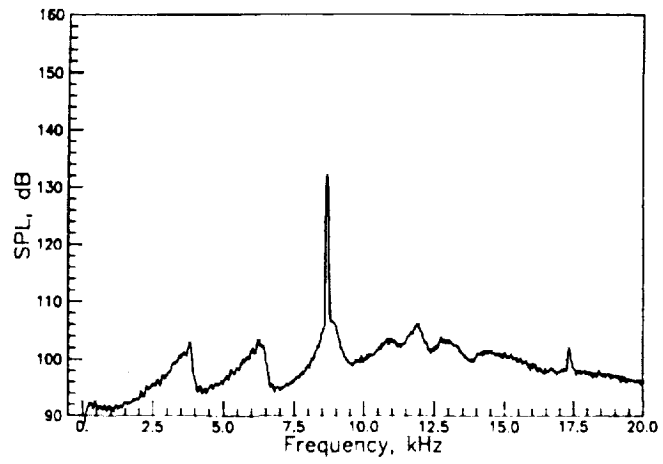


(b) $R/D=2.000$

Figure 48. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.07$.

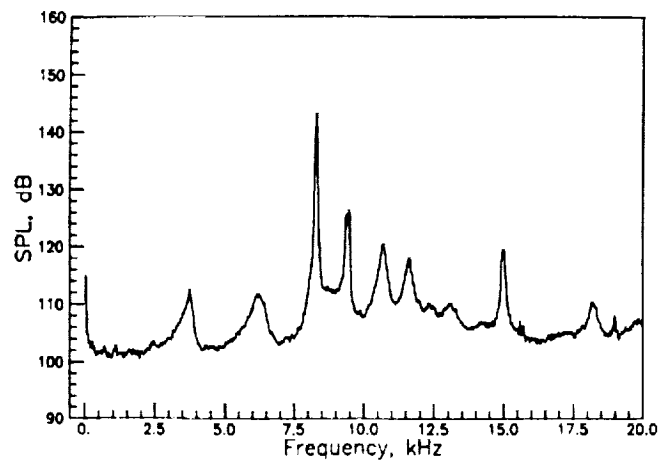


(a) $R/D=0.642$

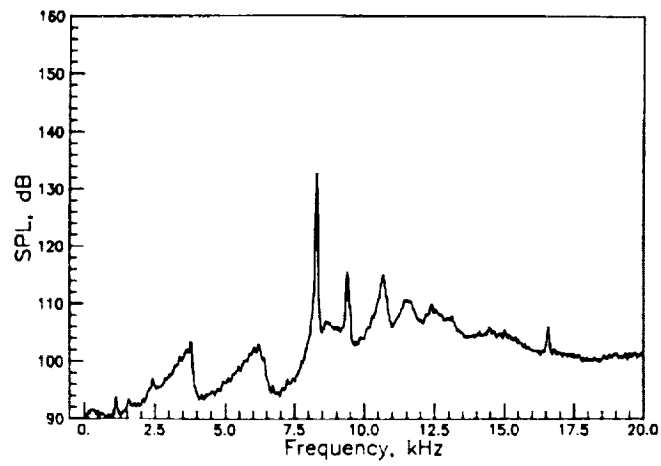


(b) $R/D=2.000$

Figure 49. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.09$.

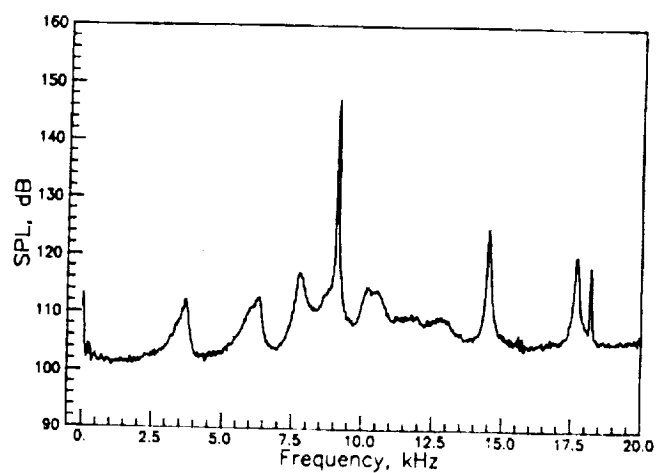


(a) $R/D=0.642$

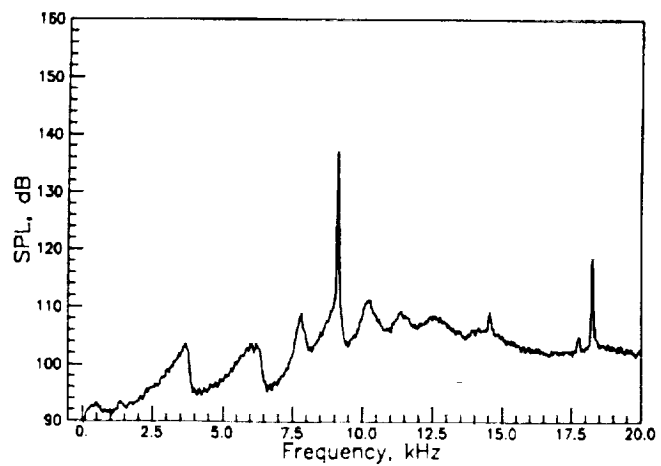


(b) $R/D=2.000$

Figure 50. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.11$.

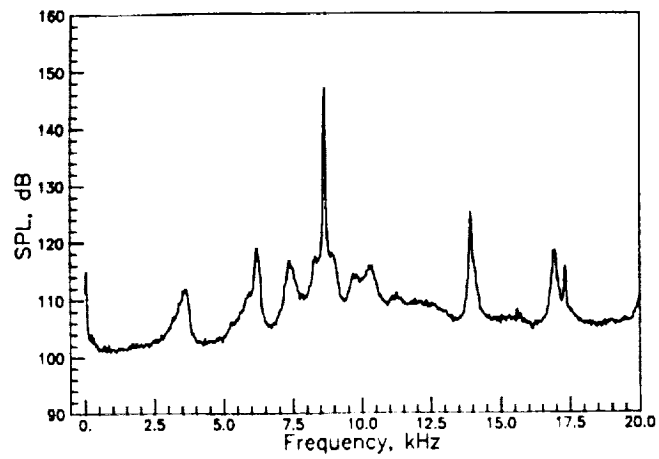


(a) $R/D=0.642$

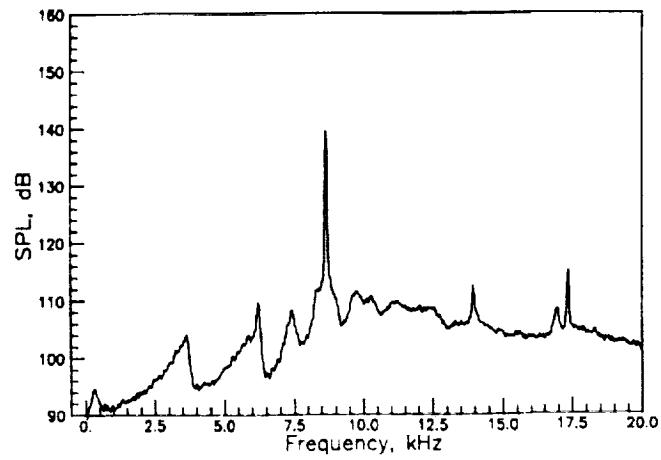


(b) $R/D=2.000$

Figure 51. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.13$.

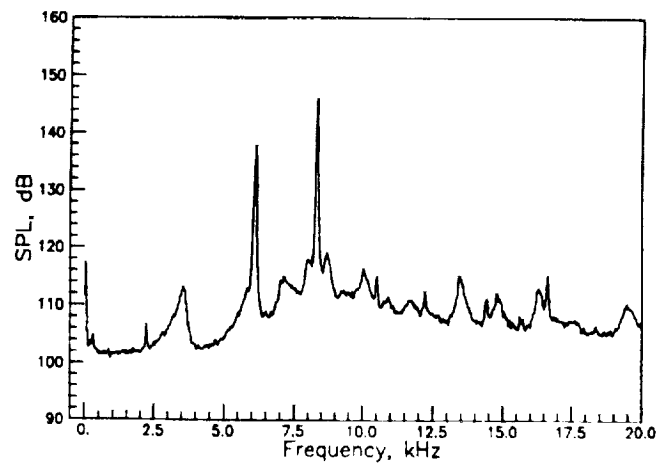


(a) $R/D=0.642$

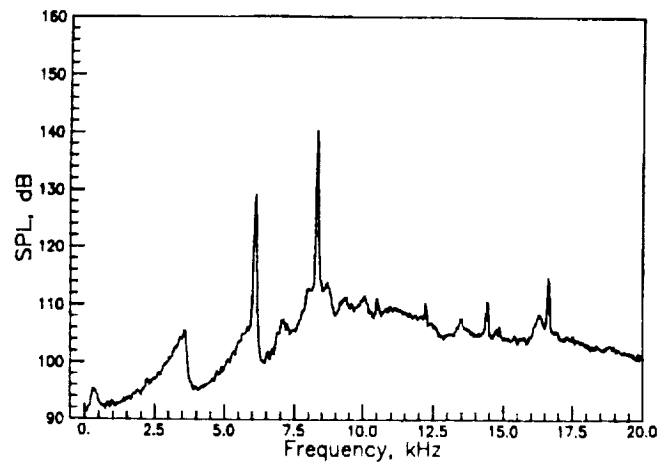


(b) $R/D=2.000$

Figure 52. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.15$.

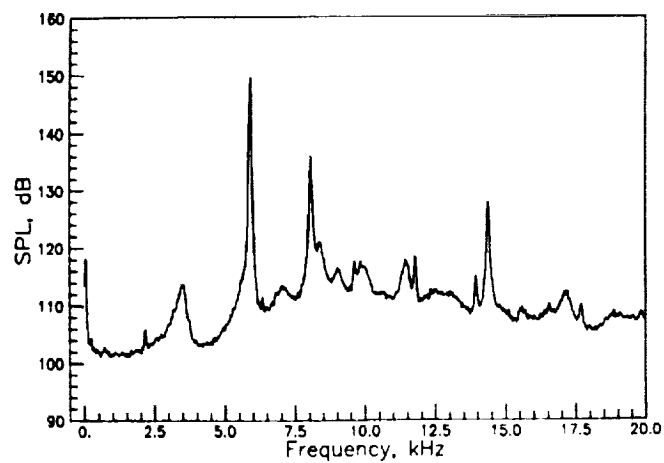


(a) $R/D=0.642$

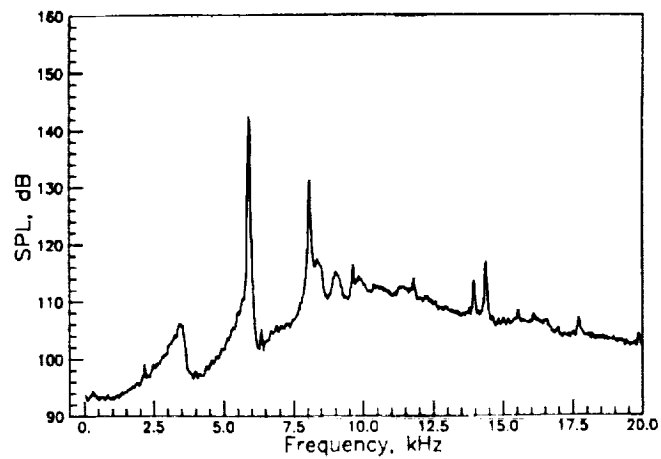


(b) $R/D=2.000$

Figure 53. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.17$.

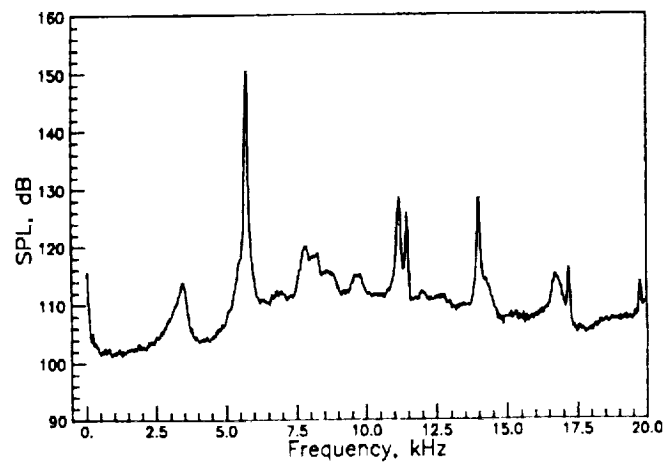


(a) $R/D=0.642$

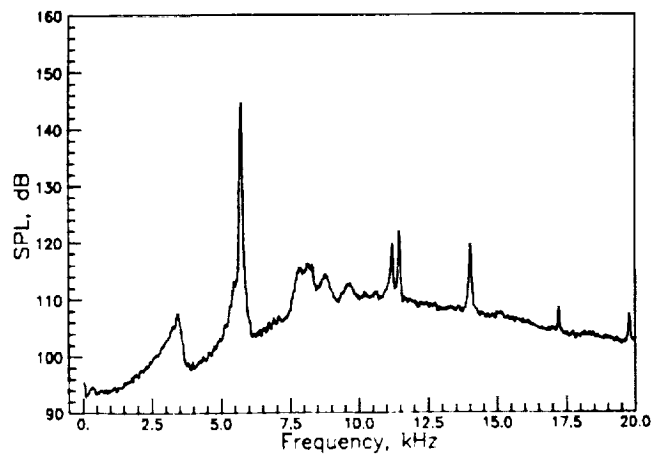


(b) $R/D=2.000$

Figure 54. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.19$.

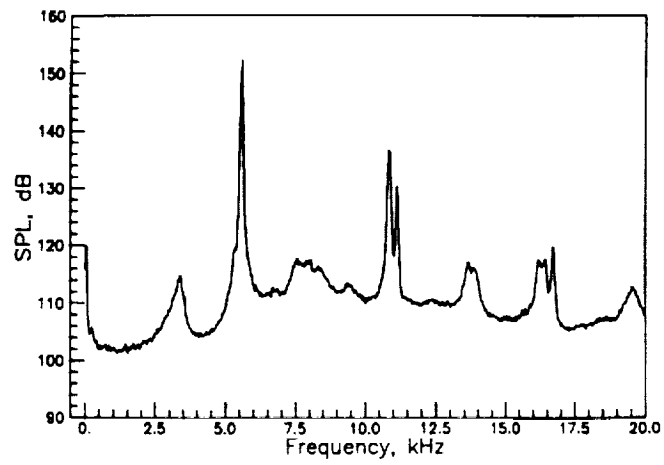


(a) $R/D=0.642$

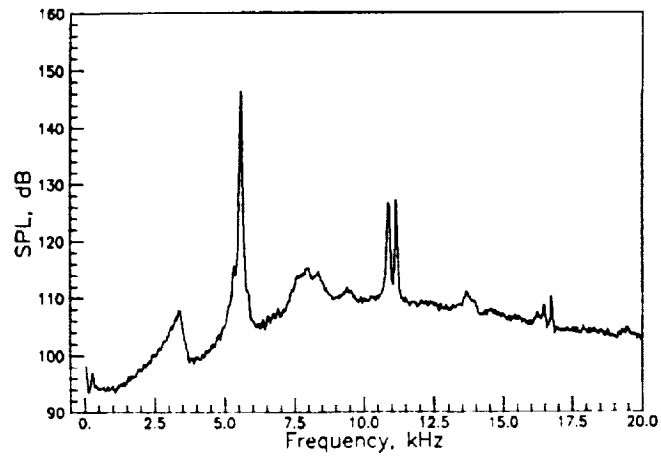


(b) $R/D=2.000$

Figure 55. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.21$.

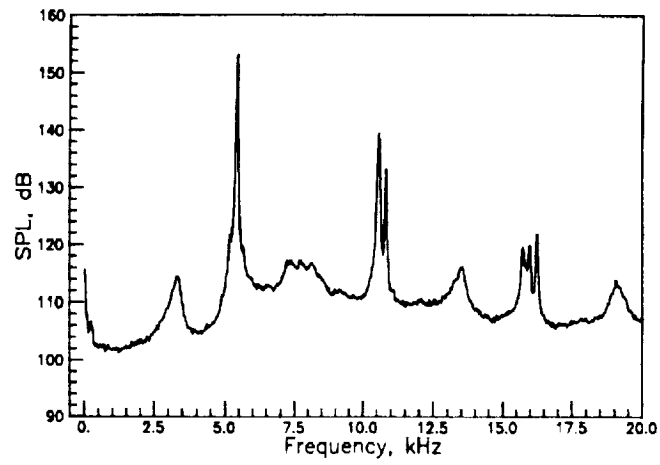


(a) $R/D=0.642$

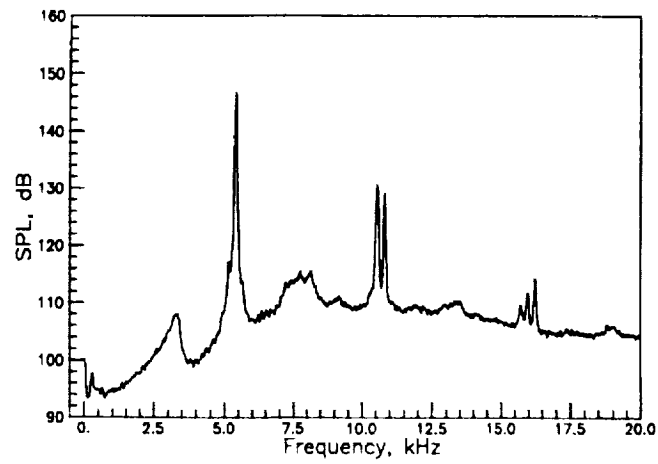


(b) $R/D=2.000$

Figure 56. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.23$.

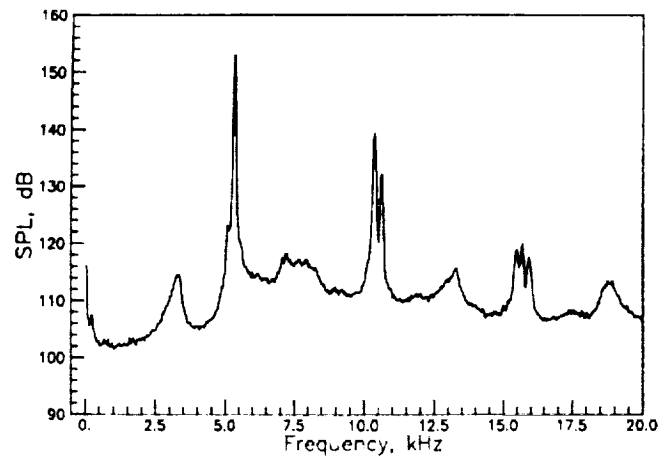


(a) $R/D=0.642$

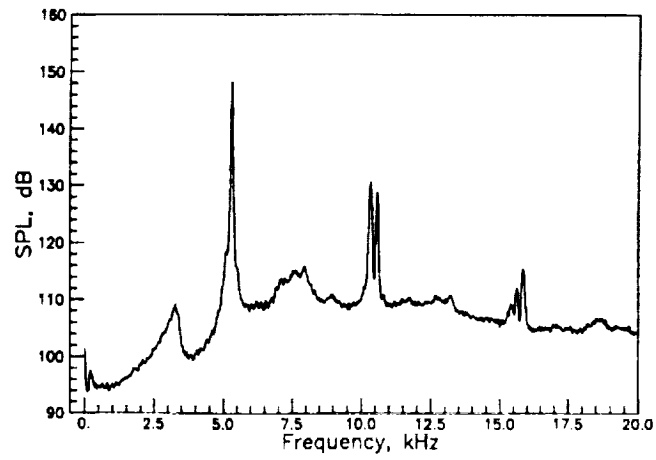


(b) $R/D=2.000$

Figure 57. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.25$.

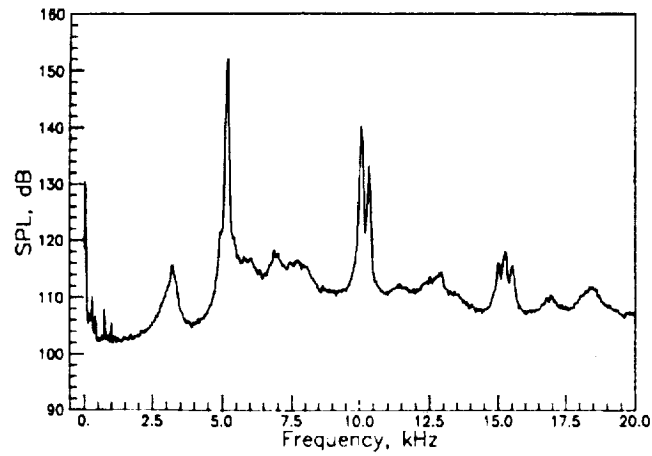


(a) $R/D=0.642$

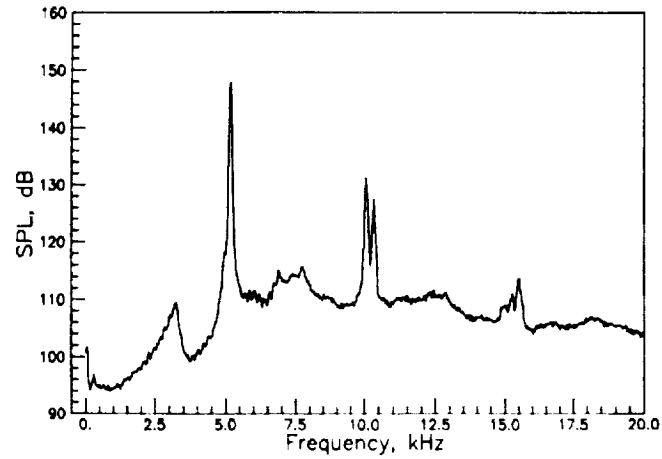


(b) $R/D=2.000$

Figure 58. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.27$.

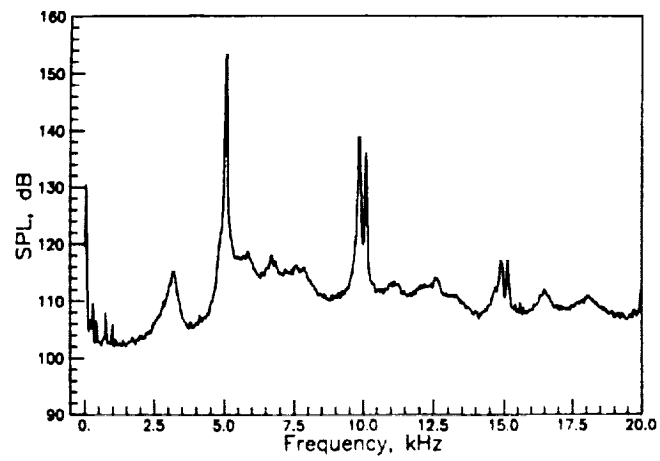


(a) $R/D=0.642$

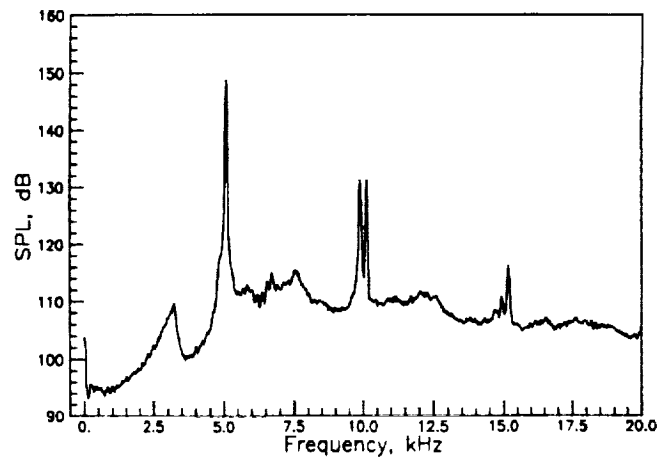


(b) $R/D=2.000$

Figure 59. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.29$.

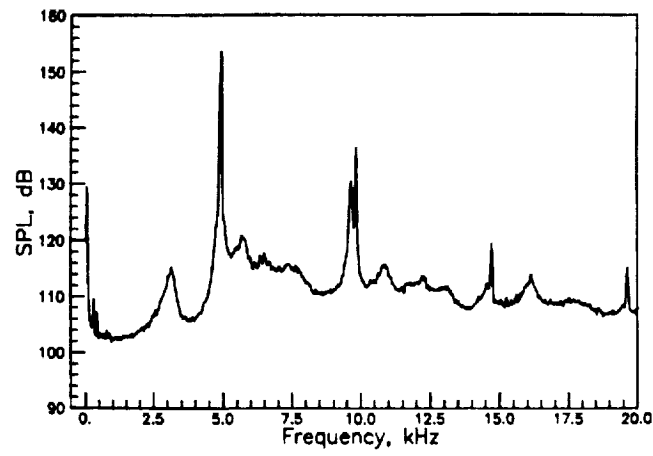


(a) $R/D=0.642$

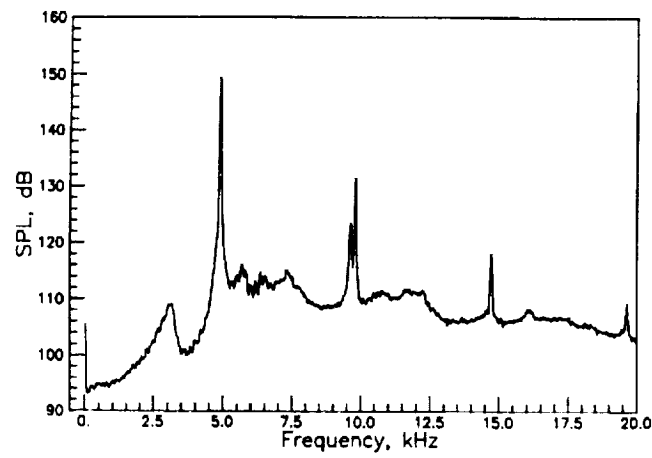


(b) $R/D=2.000$

Figure 60. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.31$.

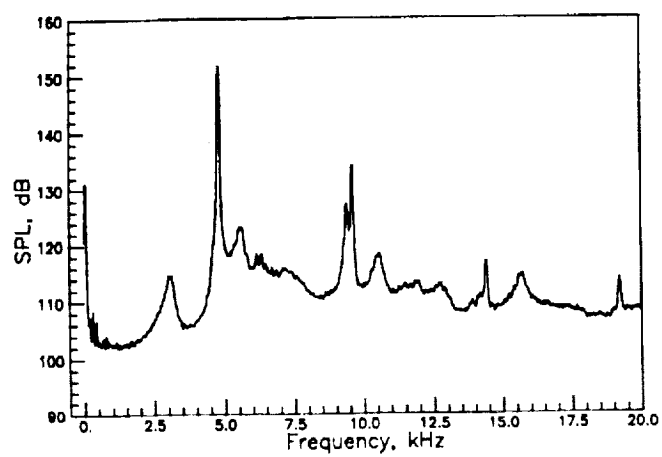


(a) $R/D=0.642$

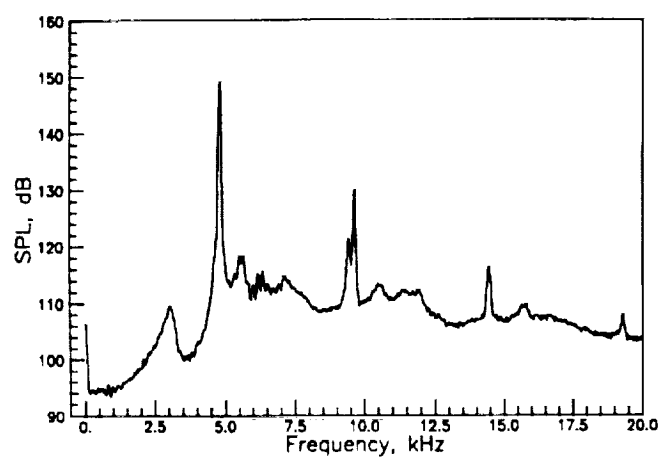


(b) $R/D=2.000$

Figure 61. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.33$.

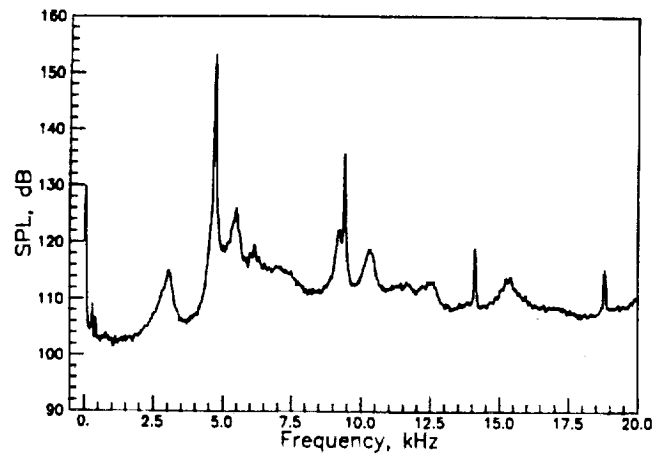


(a) $R/D=0.642$

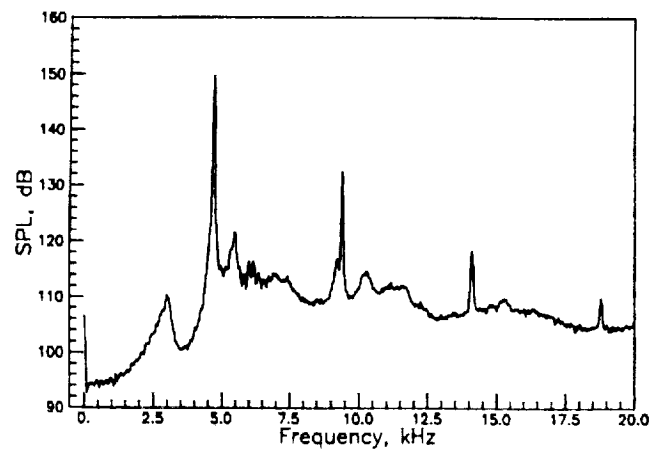


(b) $R/D=2.000$

Figure 62. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.35$.

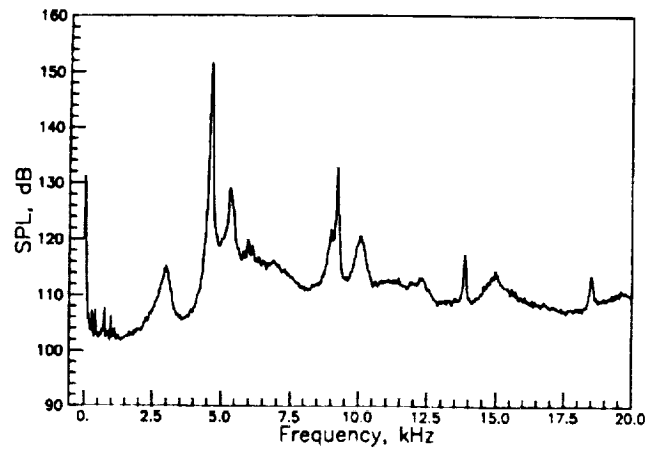


(a) $R/D=0.642$

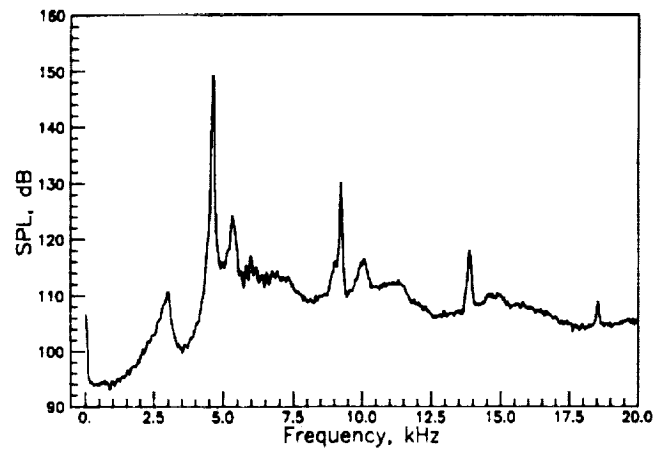


(b) $R/D=2.000$

Figure 63. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.37$.

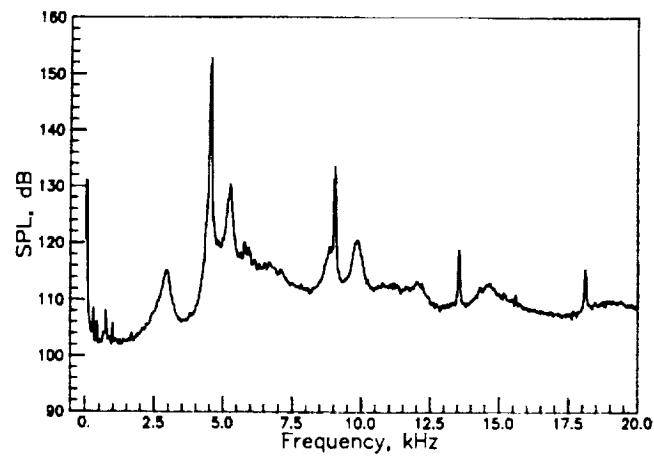


(a) $R/D=0.642$

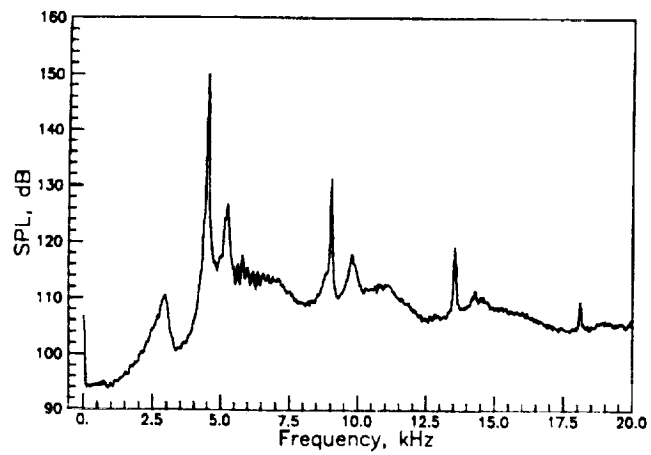


(b) $R/D=2.000$

Figure 64. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.39$.

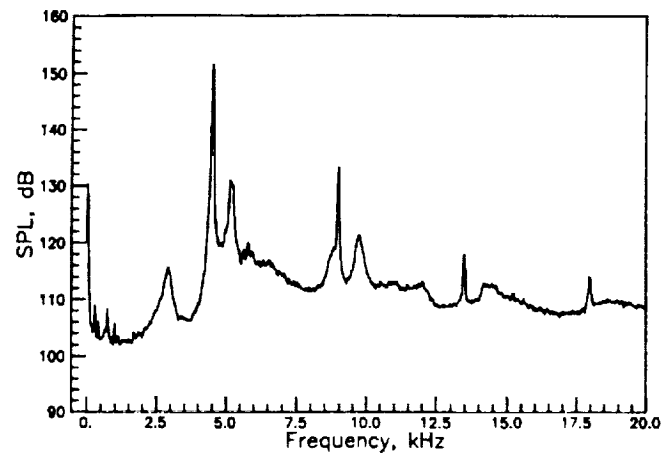


(a) $R/D=0.642$

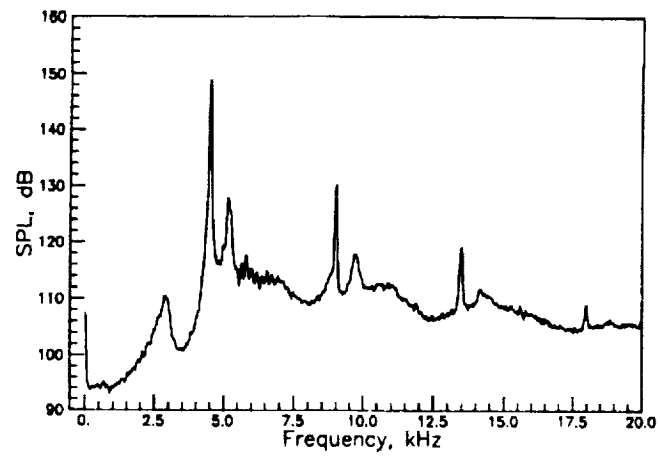


(b) $R/D=2.000$

Figure 65. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.41$.

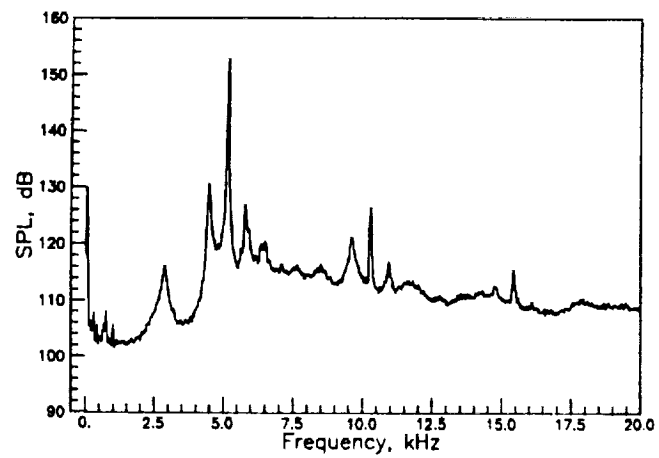


(a) $R/D=0.642$

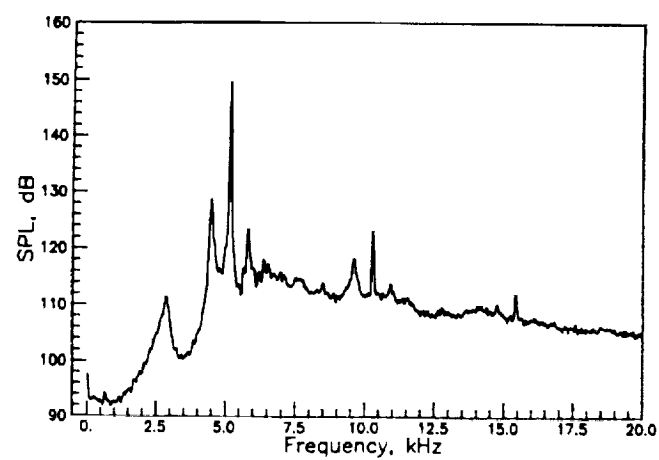


(b) $R/D=2.000$

Figure 66. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.42$.

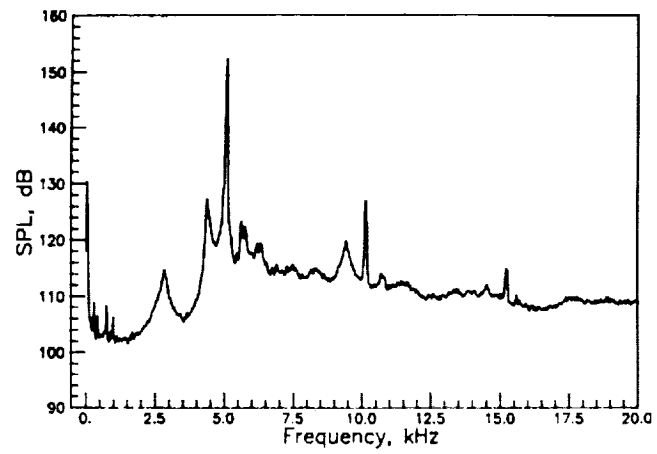


(a) $R/D=0.642$

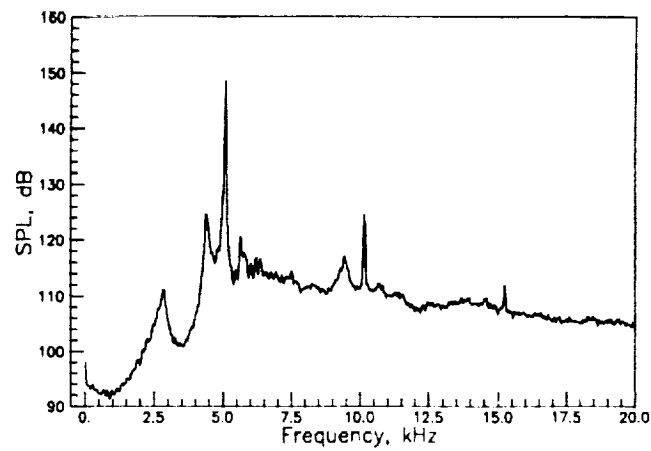


(b) $R/D=2.000$

Figure 67. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.44$.

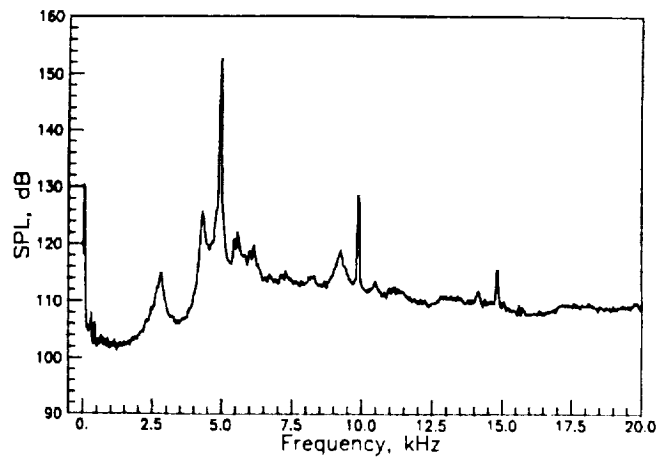


(a) $R/D=0.642$

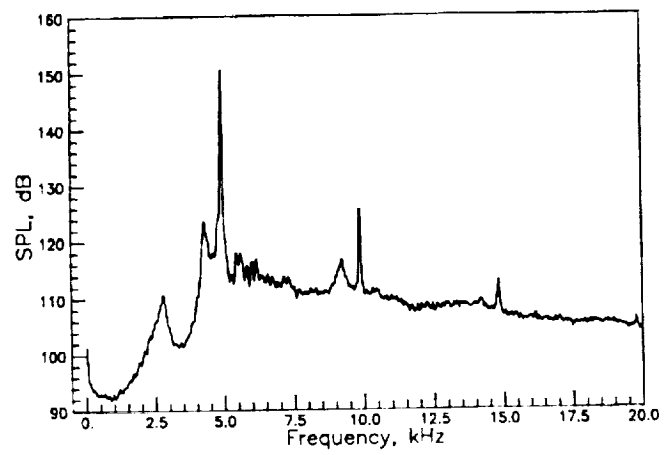


(b) $R/D=2.000$

Figure 68. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.46$.

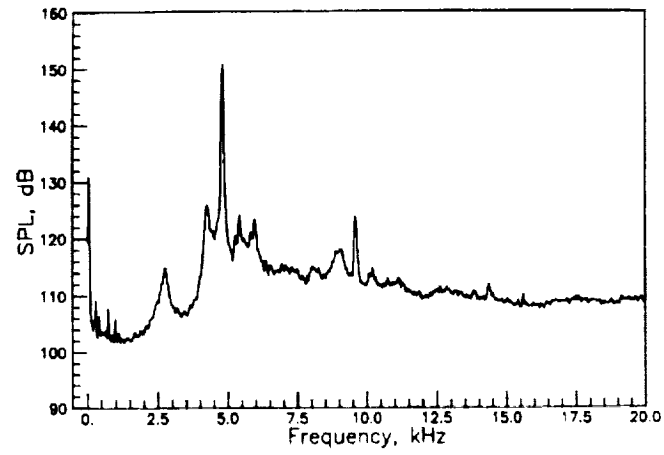


(a) $R/D=0.642$

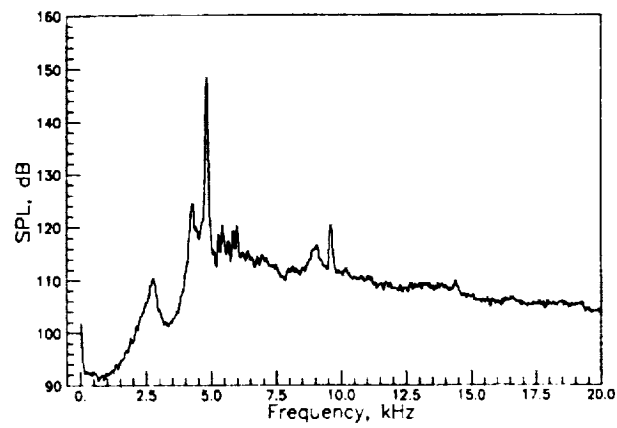


(b) $R/D=2.000$

Figure 69. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.48$.

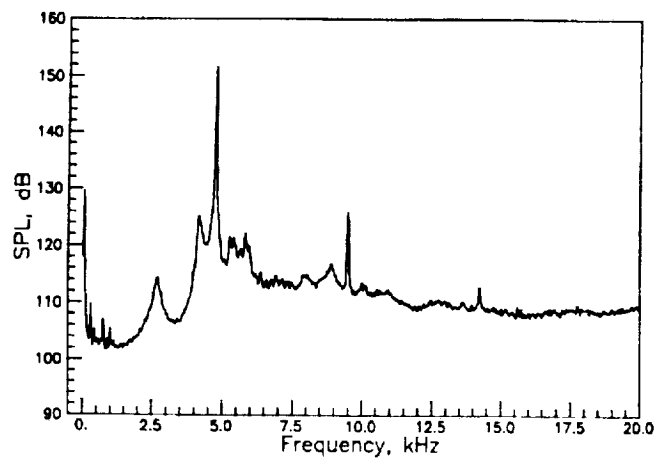


(a) $R/D=0.642$

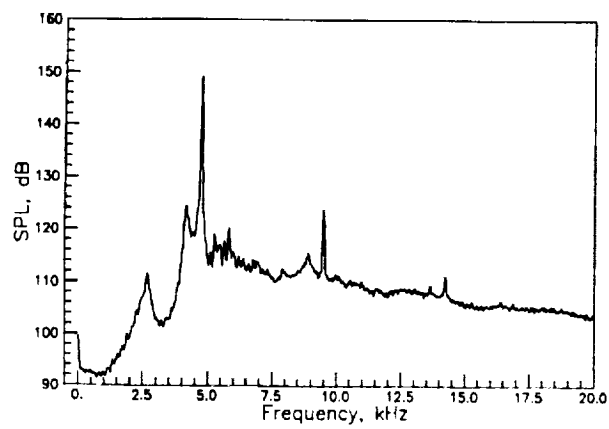


(b) $R/D=2.000$

Figure 70. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.50$.

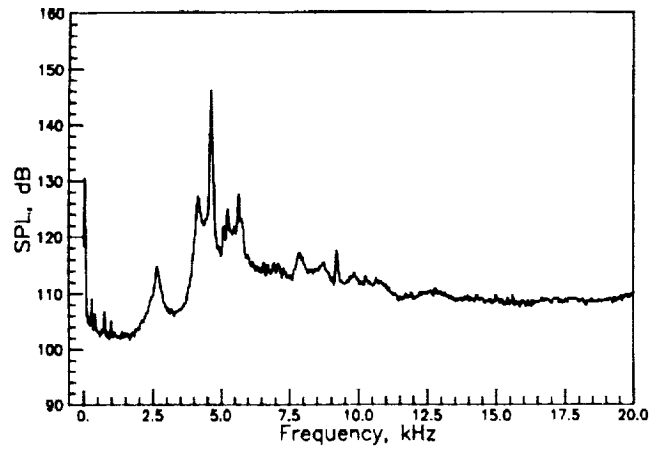


(a) $R/D=0.642$

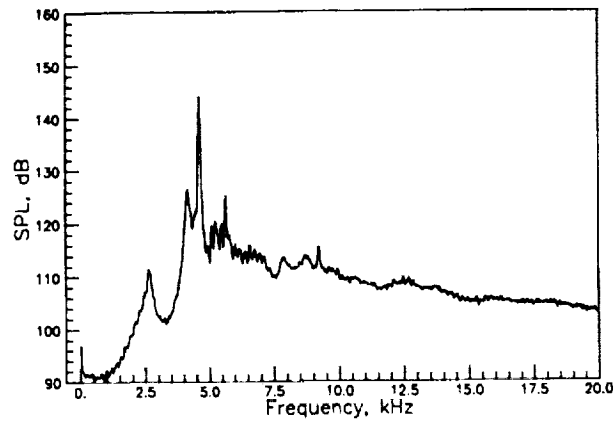


(b) $R/D=2.000$

Figure 71. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.52$.

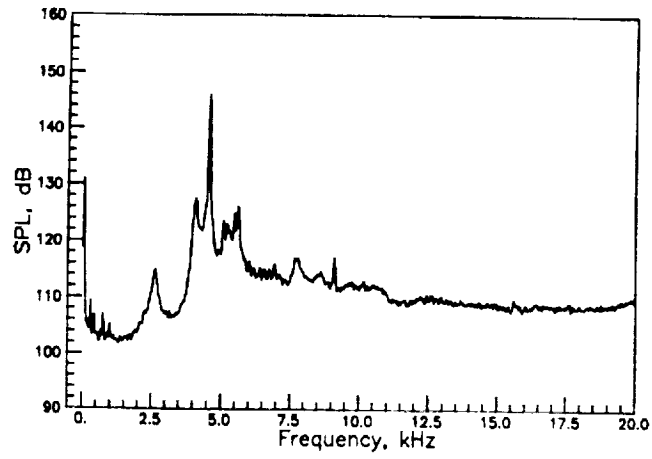


(a) $R/D=0.642$

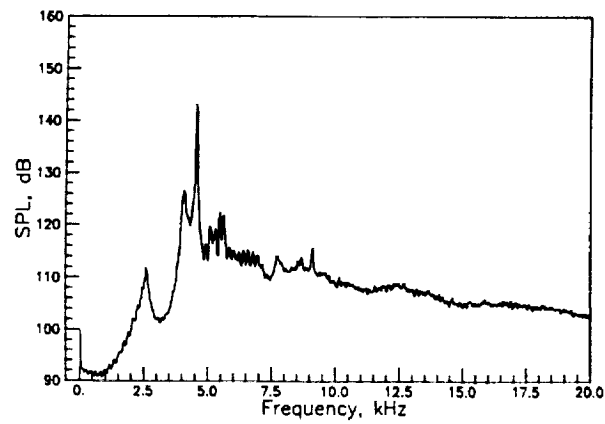


(b) $R/D=2.000$

Figure 72. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.54$.

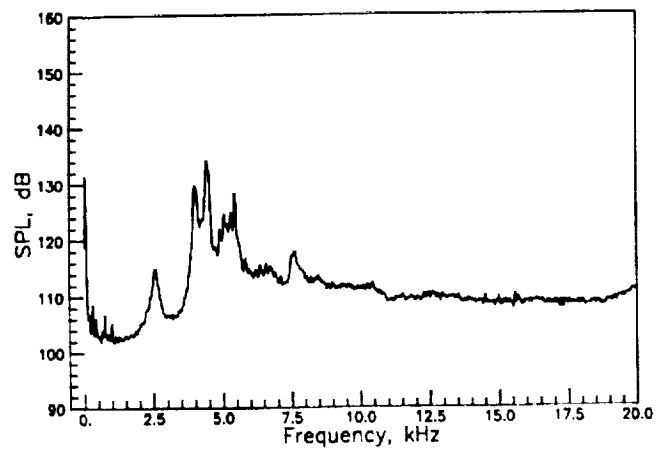


(a) $R/D=0.642$

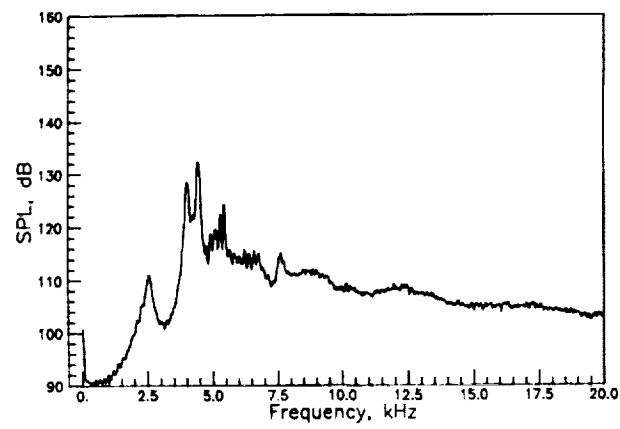


(b) $R/D=2.000$

Figure 73. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.56$.

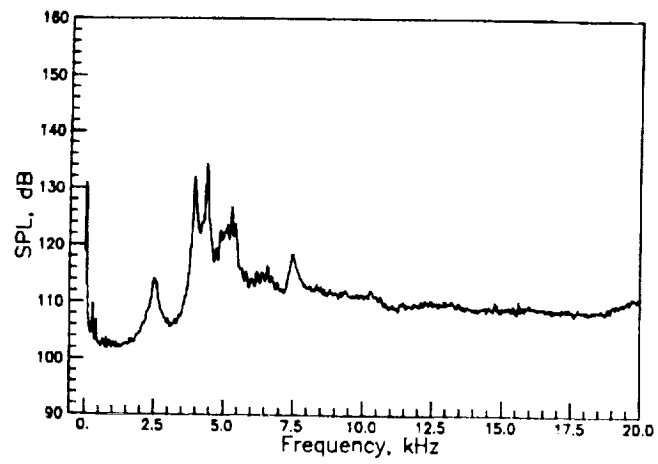


(a) $R/D=0.642$

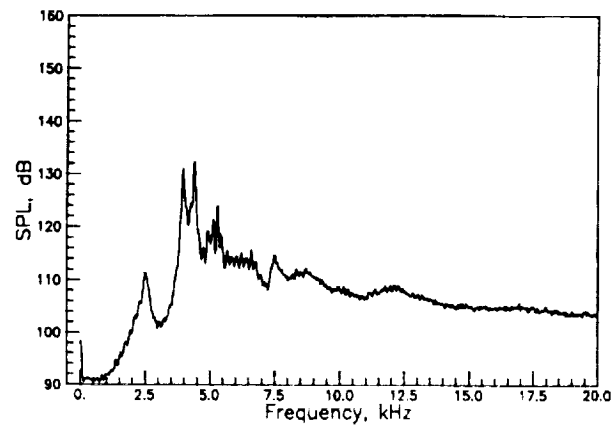


(b) $R/D=2.000$

Figure 74. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.58$.

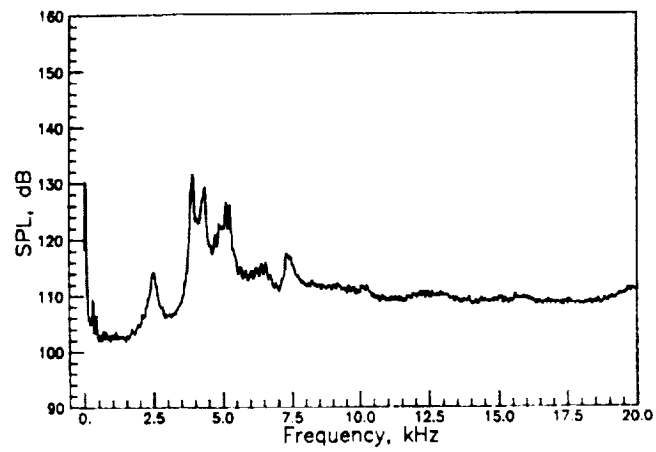


(a) $R/D=0.642$

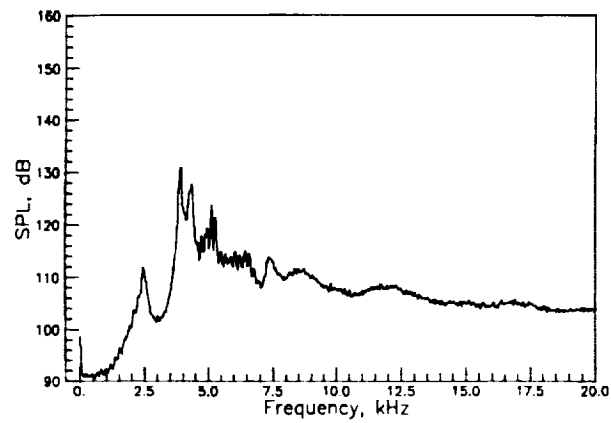


(b) $R/D=2.000$

Figure 75. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.60$.

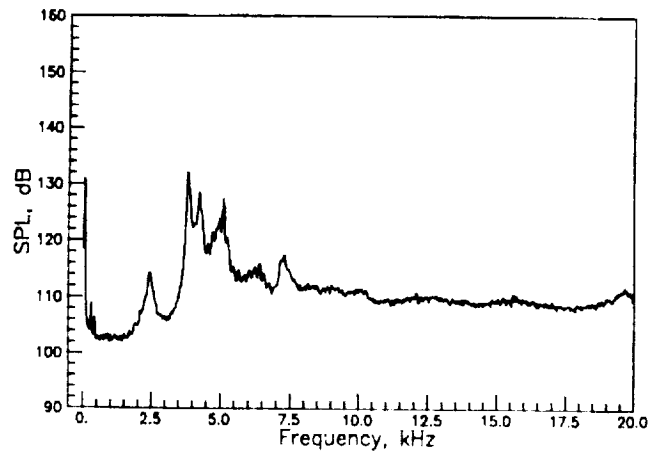


(a) $R/D=0.642$

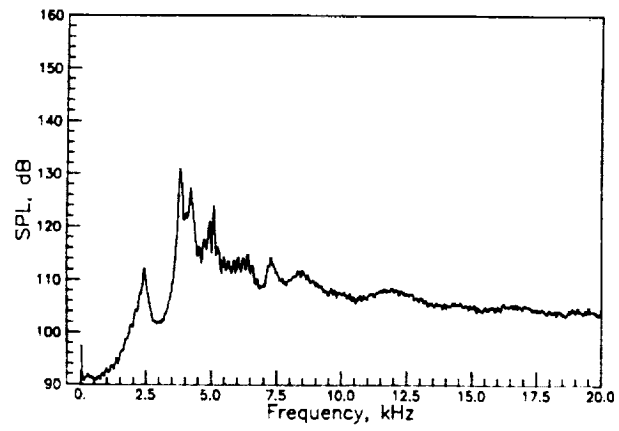


(b) $R/D=2.000$

Figure 76. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j=1.62$.

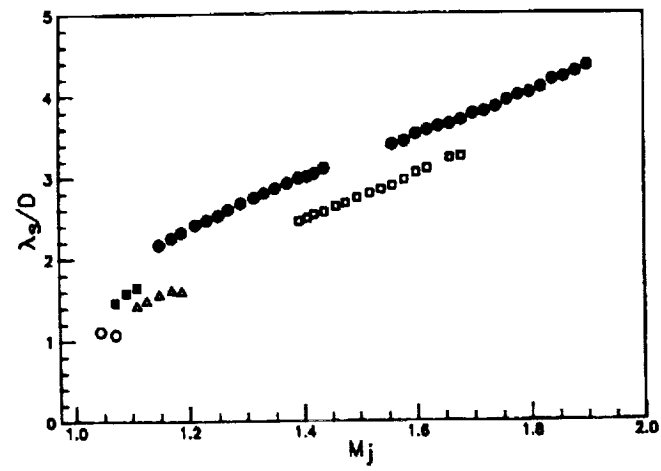


(a) $R/D=0.642$

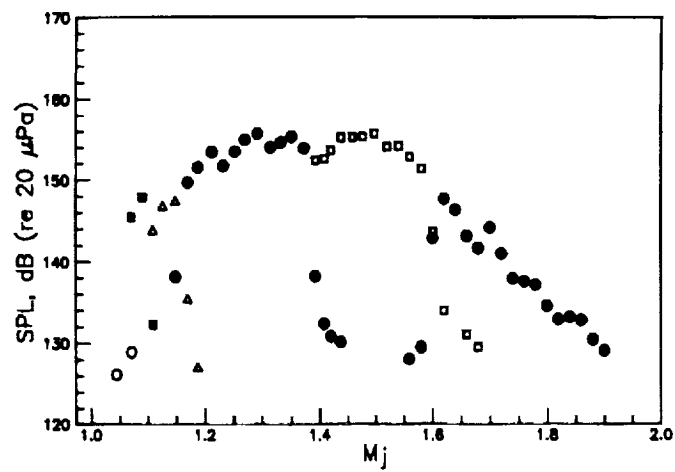


(b) $R/D=2.000$

Figure 77. Narrowband spectra for the 0.200 inch lip thickness nozzle at $M_j = 1.64$

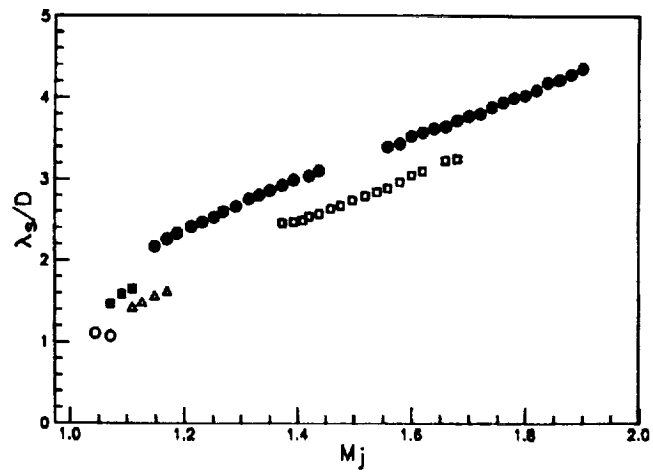


(a) Normalized acoustic wavelength

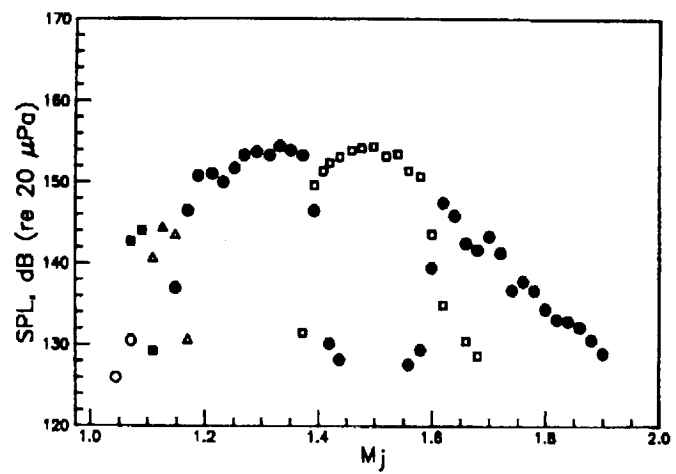


(b) Sound pressure level

Figure 78. Dominant screech components for 0.625 inch lip thickness nozzle at $R/D=0.642$.

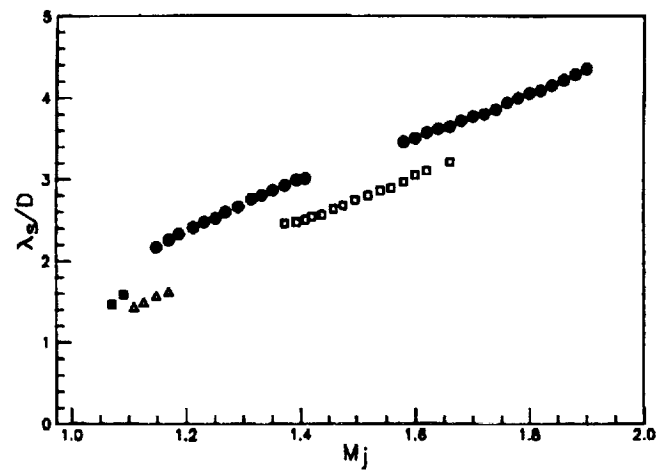


(a) Normalized acoustic wavelength

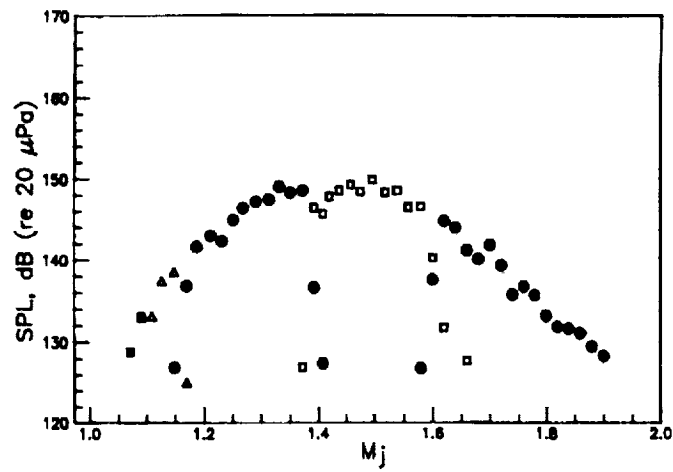


(b) Sound pressure level

Figure 79. Dominant screech components for 0.625 inch lip thickness nozzle at $R/D=0.889$.

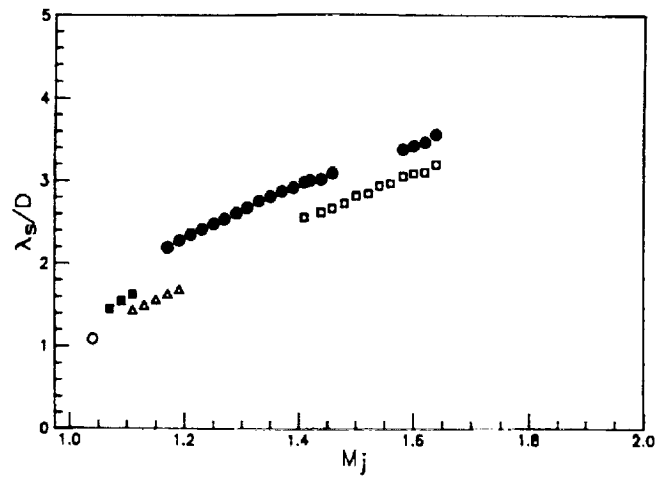


(a) Normalized acoustic wavelength

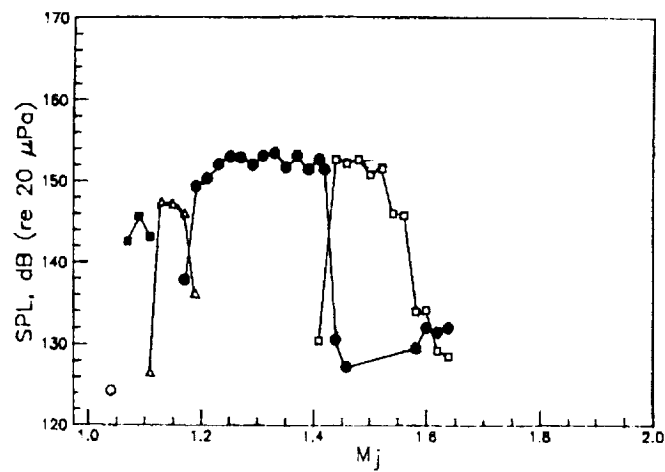


(b) Sound pressure level

Figure 80. Dominant screech components for 0.625 inch lip thickness nozzle at $R/D=2.000$.

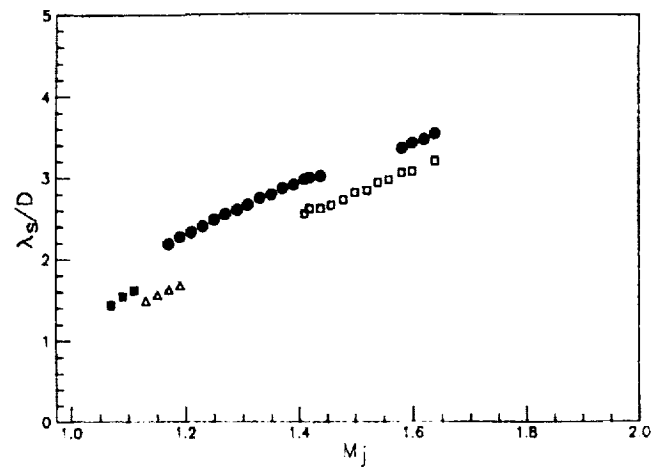


(a) Normalized acoustic wavelength

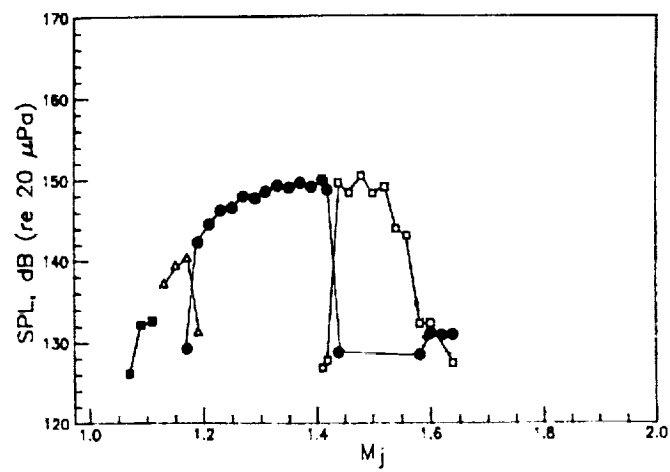


(b) Sound pressure level

Figure 81. Dominant screech components for 0.200 inch lip thickness nozzle at $R/D=0.642$.



(a) Normalized acoustic wavelength



(b) Sound pressure level

Figure 82. Dominant screech components for 0.200 inch lip thickness nozzle at $R/D=2.000$.

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